

ORBIT-SPECTRUM SHARING BETWEEN THE FIXED-SATELLITE AND BROADCASTING-SATELLITE SERVICES WITH APPLICATIONS TO 12 GHz DOMESTIC SYSTEMS

PREPARED FOR THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

EDWARD E. REINHART

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PREFACE

This is the final report on Tasks 1, 2, and 3 of a modification to NASA contract NAS5-21722--titled "A Study of Spectrum and Orbit Sharing Between the Broadcasting-Satellite Service and the Fixed-Satellite Service in the 11.7 to 12.2 GHz Band." The final report on other tasks of this contract will appear as Rand report R-1300-NASA, *Planning and Coordination of Broadcasting-Satellite Systems*.

The study reported here was sponsored by NASA as a part of their technical consultation program. It was motivated by an FCC request to NASA for technical guidance regarding preferred methods for sharing the 11.7 to 12.2 GHz band between the fixed-satellite and broadcasting-satellite services. The results of the study should be useful to the FCC in connection with its domestic regulatory responsibilities in this frequency band. The analytic techniques and results are also relevant to the formulation of U.S. positions in preparation for the 1977 planning conference of the International Telecommunication Union (ITU), which will develop international plans for the use of the 12 GHz broadcasting-satellite band and for the 1979 ITU World Administrative Radio Conference, which will revise the entire frequency allocation table.

Although the emphasis is on domestic systems in the 11.7 to 12.2 GHz band, the report provides a systematic, tutorial analysis of the general problem of orbit-spectrum sharing among inhomogeneous satellite systems. Building upon the pioneering studies of orbit-spectrum utilization sponsored by the Office of Telecommunications Policy and upon the NASA analysis of domestic fixed-satellite system compatibility, it gives all of the equations needed in the analysis and summarizes and interprets the relevant experimental data. Particular attention is paid to the problem of extrapolating and applying the available data on rain attenuation and to reconciling differences in the results of various measurements of the subjective effects of interference on television picture quality.

An analytic method is presented to replace "trial-and-error" for determining the approximate values of the intersatellite spacings required to keep mutual interference levels within prescribed limits when many dissimilar satellites share the orbit. Another powerful and essential analytic tool developed for this study is an efficient new computer model for assessing the interference compatibility of arbitrary configurations of large numbers of geostationary satellite systems. Although the computer model presently is restricted to telephone and television signals that employ frequency modulation, it is not restricted to the 12 GHz band, and could easily be extended to include other modulation techniques.

New concepts and terminology are introduced for describing and evaluating sharing strategies. For example, the terms "spectrum division" and "orbit division" are used to distinguish between strategies in which each satellite service can use only an assigned share of the spectrum or orbit, respectively, while enjoying unrestricted access to the other components of the orbit-spectrum resource. The concept of "utilization factor" is defined as a dimensionless measure of the effectiveness with which a service utilizes its share of the resource. The sum of the utilization factors for the sharing services then yields the "total utilization factor," which affords a useful figure-of-merit for the sharing strategy under investigation.

Each section of the report is complete in itself. Readers who are not interested in the technical basis for the analysis may safely omit Secs. III, IV, V, and the Appendix and concentrate on the detailed description of the problem contained in Sec. II, the evaluation of sharing strategies in Sec. VI, and the discussion of conclusions in Sec. VII.

SUMMARY

In the United States, the band 11.7 to 12.2 GHz was recently allocated to both the fixed-satellite and broadcasting-satellite services. For these services to share the allocation equitably and efficiently, the design and deployment of future systems will have to be carefully regulated. To provide a technical basis for developing the necessary rules and regulations, this report identifies and evaluates a number of strategies for sharing the orbit-spectrum resource consisting of the 500 MHz of spectrum in the band and a nominal 75 deg segment of the geostationary orbit.

The analytic approach begins with the design of a set of four baseline system models to represent the two services, taking care to ensure that the choice of parameters for these systems is based on consistent design assumptions. Alternative sharing strategies are applied to various mixes of the baseline systems using computer simulation to verify the interference compatibility of the assumed satellite system configurations. The strategies are evaluated in terms of the effectiveness with which each service utilizes its share of the orbit-spectrum resource. The measure of effectiveness is the "utilization factor," defined as the capacity that a service can provide when using an assigned share of the resource relative to the capacity it could provide if granted an exclusive allocation of the entire resource. The sum of the utilization factors for the two services is the "total utilization factor," which is taken as a figure-of-merit for the sharing strategy.

Two types of sharing strategies are considered. In a spectrum-division strategy, each service can occupy the entire orbital segment but is assigned only part of the frequency band. In an orbit-sharing strategy, the reverse is true. The principal conclusions to be drawn from a comparison of these strategies are as follows:

The fixed-satellite and broadcasting-satellite services can share the orbit-spectrum resource equitably and effectively. Both orbit-division and spectrum-division strategies permit total utilization

factors close to 100 percent, indicating that sharing does not significantly jeopardize orbit-spectrum utilization.

With spectrum-division there is no interservice interference so that the utilization factor for each service is very nearly proportional to the fraction of spectrum allocated to it and the total utilization factor is always near 100 percent. The spectrum may be divided between the services in any desired proportion independent of the characteristics of the satellite systems.

With orbit-division, interservice interference is controlled by careful separation of satellites in the orbit and the preferred satellite deployment depends on both the equipment and signal parameters of the sharing systems. However, the problem differs only in degree from that of finding compatible spacings for intraservice sharing and, for any given combination of systems, a deployment can be found for which the utilization factor of the corresponding orbit-division strategy approaches 100 percent. For certain combinations of systems, the total utilization can significantly exceed 100 percent, although in these cases, there is a limitation on the relative size of the orbit shares that can be assigned.

Compared with an orbit-division strategy using the same types of systems, spectrum-division imposes a serious economic penalty: each service has to use more satellites to provide the same total capacity. Since an orbit-division strategy can provide equally high and in some cases higher utilization factors, it is concluded that orbit-division is to be preferred to spectrum division.

The satellite deployment that characterizes the preferred orbit-division strategy for a given set of systems depends on the degree of inhomogeneity among those systems. When satellite eirps, earth-station antenna diameters, or signal modulation indices are quite different, a clustered deployment in which two or more satellites of the less powerful system are "clustered" between adjacent satellites of the more powerful system yields the highest total utilization. When the system parameters are more homogeneous, the deployment becomes less critical, and in most cases, somewhat higher utilization factors

are obtained by gathering satellites of the same kind together in clusters and minimizing the number of interfaces between clusters.

The use of sharing tactics such as frequency interleaving, crossed-polarization operation, and crossed-beam operation, do not normally affect the values of utilization factor for a particular sharing strategy because it is assumed that the same tactics are also employed for intraservice sharing when computing the capacities for exclusive allocation used to normalize the utilization factor. On the other hand, sharing tactics have a marked effect on the scale of the intersatellite spacings and hence on the total number of channels that can be provided by each service.

For a given set of systems, there will be a family of related orbit-division strategies all having the same kind of preferred satellite deployment but differing in the combination of tactics employed. The merit of a particular sharing tactic may be judged in terms of the effect it has on the spacings in the characteristic satellite deployment and on the total number of channels possible with exclusive occupancy. As a basis for comparison, the spacings and total channel capacities for each family of strategies can be given for the "basic" strategy in which frequency interleaving, crossed-polarization, and crossed-beams are not used, the telephone interference objective is 1000 pWOp, and the television protection ratio doesn't allow for "interference-masking" by noise.

For example, with the basic strategic assumptions and an appropriate division of the 75 deg of orbit between the two services, the fixed-satellite service can provide at least 200,000 simplex (100,000 duplex) telephone channels, with either of two earth stations, while the broadcasting-satellite service can provide in the order of 100 television channels for individual reception, or 200 television channels for community reception. These capacities are roughly equal to the aggregate capacity of the 20 domestic fixed-satellite systems originally planned for the 4 and 6 GHz bands. They are also quite comparable to the U.S. demand for all satellite services projected to 1980 by one analysis of future market potential.

The foregoing basic capacities can be increased significantly by including additional sharing tactics in the basic strategy appropriate to each mix of systems. Thus, if alternate polarization is used on all adjacent satellites in the deployment, parametric analysis, verified by computer simulation, shows that spacings can be cut in half and the total capacities doubled. If carrier-frequency interleaving is used in addition to crossed polarization, the capacity of each satellite will be doubled and the total capacity, compared with the base case, quadrupled.

Since there is little likelihood of interference from terrestrial systems in the 11.7 to 12.2 GHz band in the United States, the interference objective for fixed-satellite links could be doubled to 2000 pWOp with an accompanying 24 percent decrease in spacing and increase in capacity for this service. If the protection ratio for individual reception is lowered by 6 dB to account for the masking of interference by noise at the 43 dB output signal-to-weighted noise level assumed for this type of service, the number of channels could be more than doubled.

If the positions of broadcasting satellites with nonoverlapping service areas are arranged to yield crossed-path operation, as described in Sec. V, the spacing of those satellites can be reduced by as much as 30 percent with a corresponding increase in total channel capacity.

The use of sidelobe reduction techniques on earth-station antennas can yield further spacing reductions and capacity increases if the sidelobe suppression is greater than the single-entry protection ratio for interference from adjacent satellites after proper allowance for differences in eirp, frequency offset, and satellite antenna directivity. In a computer simulation involving fixed satellites with 32 ft earth-station antennas and broadcasting satellites with 3 ft antennas, the capacity increase was about 30 percent.

Although the methods and results developed in this study provide the technical basis for developing an effective orbit-spectrum plan for domestic 12 GHz fixed- and broadcasting-satellite systems, it is considered premature to draw up such a plan at this time.

More exact knowledge is needed and should be developed in a number of areas including the nature, diversity, and magnitude of potential future demands in the two services, the values of interference protection ratios to be adopted for television transmission, the permissible interference levels in telephone channels, the antenna patterns and sidelobe polarization discrimination that can be realized in practice, system margins for rainfall, and the effect on orbit-spectrum utilization of using digital modulation techniques in both services.

ACKNOWLEDGMENTS

The efficient new computer program for modeling the interference performance of arbitrary deployments of dissimilar satellite systems (described in the Appendix to this report) was written by Mrs. Marianne Lakatos. In addition, Mrs. Lakatos keypunched all of the input data and ran the program for the many sharing configurations considered in the report. These major contributions to the study are gratefully acknowledged.

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I. INTRODUCTION

In January 1973, the U.S. National Table of Frequency Allocations⁽¹⁾ was revised to reflect changes in the international allocation table that were to become effective that month. One of these revisions provides that the frequency band from 11.7 to 12.2 GHz is to be shared on an equal basis by domestic systems in both the fixed-satellite and the broadcasting-satellite services. The allocation is an important one to both services. In the case of the broadcasting-satellite service, which hitherto had no frequency allocations at all, it provides enough spectrum for extensive future development of operational systems using technology currently under development. In the case of the fixed-satellite service, the allocation offers a useful alternative to the 3.7 to 4.2 GHz band which will become increasingly crowded as Canadian and U.S. domestic fixed-satellite systems are put into operation.

To ensure that U.S. systems in the two services enjoy an equal opportunity to use this new joint allocation despite an anticipated earlier demand for fixed-satellite systems, and also to ensure that each service uses the allocation efficiently, it will be necessary for the Federal Communications Commission (FCC) to set forth rules governing the design and deployment of operational systems. The principal purpose of the study reported here is to identify, compare, and evaluate some of the alternative sharing strategies that might be considered in developing the needed rules. The scope of the study and the approach used may be inferred from the following synopsis of the report.

Section II describes the sharing problem in its general and specific aspects. It reviews the pertinent international and domestic radio regulations, introduces the general concepts for analyzing the problem and selecting a solution, describes the specifics of the problem in some detail, and outlines the simplifying assumptions introduced for purposes of analysis.

Section III is concerned with the characteristics of the fixed-satellite and broadcasting-satellite systems that might be developed

for the 12 GHz band. In particular, the design of rf links to meet applicable noise objectives in the face of fading is discussed, data on the fading statistics at 12 GHz are introduced, and specific reference or baseline system designs are postulated for use in evaluating sharing strategies.

Section IV turns to the problem of predicting the interference that arises in a sharing environment. It presents equations for computing the effects of interference on the quality of the messages carried by fixed- and broadcasting-satellite systems in terms of the signal, hardware, and geometrical parameters that describe the rf links of these systems. Also given are detailed models of the antenna patterns needed in the computations.

Section V uses the equations of the preceding section as the basis for a detailed discussion of the relative effectiveness of the various sharing tactics--i.e., the elements of system design and deployment that reduce intersystem interference and thus enhance orbit and spectrum utilization. Special attention is given to the effects on satellite spacing of various kinds of system inhomogeneities and the advantages to be gained from careful coordination of the frequencies and polarizations of interfering links.

Section VI identifies a number of different sharing strategies and applies them to the system models introduced in Sec. III. The comparative performance of these strategies in terms of simple quantitative measures of orbit and spectrum utilization is evaluated both parametrically and through application of a comprehensive new computer simulation program.

Section VII summarizes the conclusions to be reached from the sharing strategy comparison, and suggests a number of subjects for further investigation.

A detailed description and listing of the computer program for determining the interference performance of specific configurations of fixed- and broadcasting-satellite systems is given in an Appendix.

II. THE SHARING PROBLEM

REGULATORY ASPECTS

The interservice orbit-spectrum sharing problem in the 11.7 to 12.2 GHz band originated with and is circumscribed by the international and national radio regulations. Therefore, it is appropriate to begin this description of the problem with a review of the relevant regulations.

Historical Background

In 1963, the International Telecommunication Union (ITU) took official action to acknowledge that systems employing satellite-borne repeaters would soon become practical alternatives to purely terrestrial systems for many of the basic radio communication services. At the Extraordinary Administrative Radio Conference (EARC) of that year, satellite counterparts for several of the familiar terrestrial services, including the fixed service^{*} and the broadcasting service, were defined. Several frequency bands were allocated to what was to become the fixed-satellite service,^{**} but it was decided that operational satellite-broadcasting systems lay too far in the future to warrant allocation action by the EARC.⁽²⁾

During the next few years, several international fixed-satellite systems went into operation, a demand for domestic fixed-satellite systems developed, and it became clear that satellite systems for television broadcasting, earth exploration, and other applications were becoming economically, as well as technically, feasible. In response to these developments, the ITU in 1971 sponsored a World Administrative Radio Conference for Space Telecommunication (WARC-ST) in order to revise again the international radio regulations to accommodate the

^{*}Defined by the ITU as "A service of radiocommunication between specified fixed points."

^{**}The fixed-satellite service was originally called the communication-satellite service.

needs of satellite systems. Among many other actions, the WARC-ST refined the definitions of all the space services, provided frequencies for the first time to the broadcasting-satellite service, and extended the existing allocations of the fixed-satellite service to several new bands.^(3,4)

Service Definitions

The WARC-ST definitions of the broadcasting-satellite service and the fixed-satellite service eliminated references to passive satellites contained in the original EARC definitions, and distinguished between two types of reception in the former. In particular, the broadcasting-satellite service was defined as "A radiocommunication service in which signals transmitted or retransmitted by space stations are intended for direct reception by the general public. [Note:] In the broadcasting-satellite service, the term 'direct reception' shall encompass both individual reception and community reception."

Individual reception was defined as "the reception of emissions from a space station in the broadcasting-satellite service by simple domestic installations and in particular those possessing small antennae."

Community reception was described as "the reception of emissions from a space station in the broadcasting-satellite service by receiving equipment, which in some cases may be complex and have antennas larger than those used for individual reception, and intended for use: by a group of the general public at one location; or through a distribution system covering a limited area."

In its WARC-ST definition, the fixed-satellite service was defined as "a radiocommunication service: between earth stations at specified fixed points when one or more satellites are used; in some cases this service includes satellite-to-satellite links, which may also be effected in the inter-satellite service; for connection between one or more earth stations at specified fixed points and satellites used for a service other than the fixed-satellite service (for example, the mobile-satellite service, broadcasting satellite service, etc.)."

The International and Domestic Allocations

Frequencies allocated to the broadcasting-satellite service at the WARC-ST included the bands 2500 to 2690 MHz, 11.7 to 12.5 GHz, and 22.5 to 23 GHz to be shared with certain other services in specified geographic regions, plus exclusive worldwide allocations of the bands 41 to 43 GHz and 84 to 86 GHz. In addition, frequency assignments to television stations using frequency modulation in the broadcasting-satellite service were to be allowed in the band 620 to 790 MHz, subject to agreement between the administrations concerned and affected.

The broadcasting-satellite service allocation in the neighborhood of 12 GHz is the one of interest in this report and is shown in Table 1. In ITU Regions 1 (Europe, Africa, and the USSR) and 3 (South Asia and Australia), the allocation offers 800 MHz of spectrum for broadcasting-satellite systems but requires that such systems share frequencies on a coequal basis with the terrestrial fixed, mobile, and broadcasting services.

In Region 2 (North America, South America, and Greenland), the upper limit of the broadcasting-satellite allocation is reduced to 12.2 GHz (from 12.5 GHz), but the number of sharing services is expanded to include space-to-earth paths (downlinks) in the fixed-satellite service. Footnote 405BC to the allocation table restricts both fixed-satellite and broadcasting-satellite systems in Region 2 to domestic, as opposed to international, systems.

However, unlike the broadcasting-satellite service allocations at lower frequencies, and unlike the fixed-satellite service allocations at both lower and higher frequencies, the radio regulations do not specify a power flux density limitation on satellite emissions in the 11.7 to 12.5 GHz band.

In adapting the WARC-ST Region 2 allocation to U.S. needs,⁽¹⁾ the FCC reduced the number of services sharing the 11.7 to 12.2 GHz band on an equal basis from five to two. This was done as shown in Table 2

Table 1

INTERNATIONAL FREQUENCY ALLOCATIONS IN THE NEIGHBORHOOD OF 12 GHz

<u>Region 1</u>	<u>Region 2</u>	<u>Region 3</u>
11.7-12.5	11.7-12.2	11.7-12.2
FIXED MOBILE except aeronautical mobile BROADCASTING BROADCASTING-SATELLITE	FIXED FIXED-SATELLITE (space-to-earth) MOBILE except aeronautical mobile BROADCASTING BROADCASTING-SATELLITE 405BB 405BC	FIXED MOBILE except aeronautical mobile BROADCASTING BROADCASTING-SATELLITE 405BA
405BA	12.2-12.5 FIXED MOBILE except aeronautical mobile BROADCASTING	

405BAexisting and future fixed, mobile, and broadcasting services shall not cause harmful interference to broadcasting-satellite stations.....

405BB Terrestrial radio communication services...shall be introduced only after...approval of plans for the space....services...

405BC The use of the band...by the broadcasting-satellite and fixed-satellite services is limited to domestic systems and is subject to previous agreement between the administrations concerned andaffected...

SOURCE: International Allocation Table. (3,4)

Table 2

UNITED STATES FREQUENCY ALLOCATIONS IN THE NEIGHBORHOOD OF 12 GHz

<u>Band (GHz)</u>	<u>Service</u>	<u>Class of Station</u>
11.7-12.2	BROADCASTING-SATELLITE FIXED SATELLITE Mobile NG105	Common carrier land Common carrier mobile (except aeronautical mobile)

NG105 In the band 11.7-12.2 GHz, assignments in the Broadcasting Satellite and Fixed Satellite Services will not be made pending further order of the Commission

SOURCE: U.S. Table of Frequency Allocations. (1)

by eliminating the terrestrial fixed and broadcasting services altogether and by permitting the mobile service to use the band only on a secondary (non-interfering) basis. Along with this action, the FCC raised the important question of just how "equal sharing" between the two permitted satellite services was to be carried out.

A proposal to split the band into two sub-bands, although not necessarily of equal width, with the fixed-satellite service primary to the broadcasting-satellite service in the lower sub-band and secondary in the upper, was discussed in the preliminary FCC notice regarding the incorporation of the WARC-ST allocations into the national table.⁽⁵⁾ This proposal was subsequently dropped in response to objections by potential fixed-satellite system applicants⁽⁶⁾ who felt that a more effective arrangement would be to allocate portions of the visible geostationary orbit, rather than the frequency band, to each service.

In the final version of the U.S. Table of Frequency Allocations,⁽¹⁾ the FCC left open the question of how the 11.7 to 12.2 GHz band was to be shared by the two services. Footnote NG105 was included to prohibit assignment of frequencies to either service pending further action by the FCC.

The frequency-sharing problem implied by the allocations in the 11.7 to 12.2 GHz band is, of course, not confined to that band; to paraphrase an old adage to apply to satellite relay systems, "what comes down, must have gone up." So, before leaving the subject of allocations, it is necessary to consider briefly the frequency bands that may be used for transmitting to satellites in the fixed- and broadcasting-satellite services the signals that they will radiate back to earth in the 11.7 to 12.2 GHz band.

Since signal processing in the satellite (other than amplification and frequency shifting) is not presently contemplated for either service, the amount of spectrum required for uplinks is the same as for downlinks. Inasmuch as the uplinks for broadcasting satellites were defined to be part of the fixed-satellite service, it follows that a 500 MHz allocation to the fixed-satellite service (earth-to-space) is needed.

In the international radio regulations, the band 10.95 to 11.2 GHz is allocated to this service in Region 1 and the band 12.5 to 12.75 GHz in Regions 1 and 2. However, the only worldwide 500 MHz allocation to fixed-satellite uplinks in the neighborhood of 12 GHz is the band 14.0 to 14.5 GHz, which is to be shared equally with the radionavigation service from 14.0 to 14.3 GHz, the radionavigation-satellite service from 14.3 to 14.4 GHz, and the fixed and mobile services from 14.4 to 14.5 GHz. The U.S. allocation table further restricts sharing in this band by barring services other than the fixed-satellite service from the sub-band 14.3 to 14.5 GHz, although it does permit the space research service to use parts of the band on a secondary basis. For purposes of analysis in this report, the band 14.0 to 14.5 GHz will be adopted as the uplink counterpart to the 11.7 to 12.2 GHz band.

GENERAL CONCEPTS

Before looking at other specifics of the 11.7 to 12.2 GHz sharing problem, it will be useful to discuss some of the general concepts and quantities in terms of which the problem may be described.

Communication Needs and Message Channels

Probably the most basic component in the description of a problem involving communication systems is a characterization of the real or potential communication needs (demands, requirements) to be met by the systems. The elements of such a characterization are the "needlines" or message channels to be provided--i.e., the number, type, quality, and reliability of information channels, the locations of their end points or terminals, and the times or fraction of the time that they will be needed.

The definition of services by the ITU may be viewed as an attempt to categorize message channels according to the nature and mobility of their terminals, the number of receiving terminals to be reached from a single transmitting terminal, the operational purpose of the messages carried, and the type of relays employed. Thus, the fixed service includes all message channels between pairs of fixed points; the mobile service comprises channels between fixed points and terminals on land,

sea, and airborne vehicles; and the broadcasting service involves one-way message channels carrying programs from a few transmitters to a very large number of receivers. The satellite counterparts of these services represent subdivisions of the same categories of message channels according to the type of transmission path.

The classification of message channels by service provides a basis for dividing up the total worldwide communication needs into identifiable portions to each of which an appropriate fraction of the spectrum resource can be allocated by geographic region. The allocation process is of course a dynamic one. A block of communication needs, or more accurately, the market for the associated message channels, is closely tied to the technical and economic feasibility of the communication systems that can be built to provide the channels. A frequency allocation to one or more services should anticipate and, insofar as possible, match the needs that develop within those services during the time between allocation conferences. Fortunately, as will be seen, the capacity of a given band of frequencies in terms of message channels is an extremely flexible quantity and depends on the extent to which the rf channels within the band are reused within and among systems to provide independent message channels.

Systems and rf Links

As just noted, a frequency allocation circumscribes a communication problem to the extent of specifying the types of message channels to be provided according to services, indicating the radio spectrum that may be used by each service in various regions of the world, and sometimes imposing limitations on system parameters with the object of facilitating interservice frequency sharing. The next step in defining the problem is to partition the total demand for message channels encompassed by the allocation among independent systems.

Administrative considerations often encourage this partition to follow national and service boundaries, while economies of scale may make multinational (regional) and multiservice systems attractive. In other cases, the demand for one type of service in one nation may be so large or diverse as to encourage the development of several independent systems. As a practical matter, the number and type of message

channels to be provided by a particular system is normally determined through a cost-revenue or cost-benefit analysis by the corporation or agency underwriting the development of the system.

Whatever the basis for determining the message channels to be provided by a given system, one of the first tasks of the system designer is to decide how to group the desired message channels onto rf carriers between specified transmitting and receiving stations. Each such grouping of message channels will be referred to as an "rf link." The system as a whole may then be described in terms of the rf links that it provides or is capable of providing.

In the case of the broadcasting- and fixed-satellite systems of interest in this report, each rf link is simply a one-way communication channel formed by transmitting a single modulated carrier from one earth station via a satellite to one or more receiving earth stations within the geographic area covered by the satellite transmitting antenna beam. Thus an rf link, or simply a link, in a satellite system, consists of the tandem combination of an uplink and one or more downlinks.

A link is defined by the characteristics of its rf signal, the geometry of the signal path(s), the parameters of the equipment through which the signal passes, and the schedule, or the fraction of the time, that the link is to be available. More specifically, an rf link is described by the number and type of message channels carried and the details of how they are applied to the carrier, the locations of the transmitting earth station, the satellite, and the receiving earth station(s), and, for the uplink and each of the downlinks, by the carrier frequency, the transmitter power, the antenna patterns, polarizations, and pointing directions, and the receiving system noise temperature.

Of these several characteristics, those of the rf signal are the most definitive. Even though two links follow the same geometric path and pass through the same equipment, they are counted separately if they involve different rf signals. This is altogether appropriate, since such links can have quite different noise and interference performance, despite their other similarities.

The concept of an rf link will be elaborated further in the next subsection with examples for the two services of interest. Suffice it to say here that the key to compatible sharing and efficient use of the spectrum and the orbit lies in the design of the rf links that compose the systems that share these resources.

Sharing Tactics, Strategies, and Objectives

Careful design and coordination among rf links is especially important to satellite communication systems sharing a given frequency band because the potential capacity of the orbit and spectrum can be approached only by using the same or overlapping rf channels on many different rf links. Such frequency reuse inevitably creates mutual interference which degrades the quality of the messages carried by the links but, through proper link design and coordination, this quality impairment can be kept to acceptably low levels.

An analysis of the dependence of output message quality on the parameters of the signals, geometry, and equipment that characterize two interfering links reveals the various rules of link design and coordination that can be applied to reduce interference and to facilitate sharing. Individual rules of this sort will be called "sharing tactics." Examples include the use of opposite polarization on co-channel links to adjacent satellites, the grouping of satellites with similar characteristics in the same part of the orbit, and the suppression of sidelobes on earth-station antennas.

A coordinated set of sharing tactics applied to the design and deployment of systems will be referred to as a "sharing strategy." It is apparent that there are both intrasystem and intersystem sharing strategies. Although the same basic principles or tactics are involved in both, an intrasystem strategy is concerned primarily with rules governing the equipment parameters of the system and the deployment of its satellites relative to its earth stations. The objective of such a strategy is to satisfy a limited set of communication needs as economically as possible while keeping intrasystem interference to acceptable levels.

An intersystem sharing strategy, on the other hand, tends to take the system parameters as given and is more concerned with the relative

positions of the satellites in different systems and the coordination of carrier frequencies and polarizations of the rf signals that these systems radiate. The effectiveness of a particular intersystem sharing strategy obviously depends on the details of the systems to which it is applied. Its objectives are of course broader than those of an intrasystem strategy. Most fundamentally the objectives are to permit the systems of all nations and services that are authorized to share a given allocation to satisfy the total communication need for which the allocation was established without causing excessive intersystem interference.

Ideally, the objectives of an intersystem orbit-spectrum sharing strategy would also include the following points:

1. Ensure reasonably efficient utilization of the orbit-spectrum resource by the systems of each service.
2. Ensure that systems of each service and nation will have access to a share of this resource proportional to its foreseeable needs.
3. Permit each service to grow at its own pace and with as much design independence as is consistent with objectives 1 and 2.
4. Equalize and, to the extent possible, minimize the economic impact of sharing on each service.

In connection with objectives 3 and 4, it should be noted that a sharing strategy might include a sequence of design constraints to be applied progressively as the total number and diversity of active systems grows in time. The guideline here would be to constrain each new system only to the extent required for the maximum degree of sharing anticipated during its lifetime. An obvious problem in the practical application of such a phased strategy is its requirement for accurate long-range predictions of future systems growth.

Orbit and Spectrum Utilization

Efficient orbit-spectrum utilization has been listed as an important criterion in selecting a sharing strategy. The recommended

quantitative measure of this quantity⁽⁷⁾ is the number of channels per MHz of bandwidth and (angular) degree of orbit, based on the total capacity provided by all of the systems occupying the specified frequency band and orbital arc. To compare systems providing different types of message channels, channel capacity is sometimes expressed in terms of equivalent 4 kHz telephone channels. A television channel, for example, may be regarded as equivalent to from 800 to 1200 telephone channels in terms of the transponder capacity required for transmission.

The numerical value of the orbit-spectrum utilization achieved in a particular configuration of systems is very much dependent on the signal, geometric, and hardware parameters of the rf links that comprise those systems, and on the degree of interlink frequency and polarization coordination embodied in the sharing strategy. To judge the efficiency of a strategy for sharing the orbit-spectrum resources between two different satellite systems, an appropriate basis for comparison is the utilization factor, defined as the ratio of the utilization achieved by each kind of system to the utilization that could be achieved by that kind of system if it were to occupy the total orbit-spectrum segment exclusively. The total utilization factor is then the sum of the utilization factors achieved by each kind of system involved in the sharing. The higher the total utilization factor the more efficient the strategy. It is of particular interest to observe how the system and total utilization factors vary with the fraction of the orbit-spectrum resource assigned to each type of system in the shared configuration.

SCOPE OF THE PROBLEM

Using the concepts just described, the magnitude and complexity of the sharing problem implied by the national allocation in the neighborhood of 12 GHz will now be surveyed in greater detail, including the extent of the resource to be shared, the participants in the sharing, the nature of the communication needs, and the diversity of systems that might be built to satisfy those needs.

The Spectrum Resource

The spectrum resource to be shared is of course the 500 MHz band from 11.7 to 12.2 GHz for space-to-earth transmissions, and the 500 MHz band from 14.0 to 14.5 GHz adopted for the corresponding earth-to-space transmissions.

The eligible shareholders are the approximately 25 national administrations in ITU Region 2. Each of these countries has the right to authorize use of the 11.7 to 12.2 GHz band for domestic broadcasting-satellite systems providing community and/or individual reception and also for the downlinks of domestic fixed-satellite systems. Moreover, although the United States has restricted primary use of the 11.7 to 12.2 GHz band to these two satellite services, other countries in Region 2 may, at their option, also use the band for terrestrial systems in the fixed, mobile (except aeronautical mobile), and broadcasting services. This is relevant to U.S. use of the band because operation of satellite systems is "subject to previous agreement between the administrations concerned and those having services operating in accordance with the [frequency allocation] table which might be affected."

Similarly, the same national administrations can use the 14.0 to 14.5 GHz band for fixed-satellite service uplinks corresponding to their broadcasting-satellite and fixed-satellite downlinks in the 11.7 to 12.2 GHz band. They can also use portions of the band for the terrestrial fixed, mobile, and radionavigation services and the radionavigation-satellite services, although the United States has eliminated all but the terrestrial radionavigation service from equal sharing.

The Orbit Resource

Although the frequency bands to be shared by all Region 2 countries are the same, this is not true of the orbit resource. For a particular nation, the usable orbital arc is only that portion of the geostationary orbit visible above a specified minimum elevation angle from all potential earth-station transmitting and receiving sites within the nation. Hence the position and extent of the usable arc depends on the location and size of the country.

Figure 1 shows the usable arc corresponding to minimum elevation angles of 5 deg and 10 deg for most of the countries of the Americas. It will be noted that the greater the longitudinal extent of a nation, the narrower the range of orbital positions from which the entire nation can be served. For example, referring to Fig. 1, the orbital arc visible above 10 deg everywhere within the Continental United States is the 75 deg segment between 57 and 132 deg west longitude. Adding Hawaii reduces the usable arc to the westernmost 43 deg of this segment, and adding Alaska further reduces the usable arc segment to less than 23 deg, even if the minimum elevation angle requirement is lowered to 5 deg.

It should also be noted that, because of their comparatively smaller longitudinal width and/or more easterly location, all nations south of the United States can use portions of the arc not usable by the United States. For example, considering the arc above 10 deg elevation angle, Brazil has an orbital segment 55 deg wide which is not usable in the United States. This fact should help to eliminate possible conflicts of interest over the same orbital segment.

Several considerations relative to positioning satellites in orbit should be mentioned in this connection. First of all, when the sun passes through the beam of an earth-station receiving antenna (as it will for a few minutes of a few days near the equinoxes), it can cause a significant temporary increase in received noise power. Operators of systems containing more than one satellite may justifiably wish to separate their satellites by at least 15 deg so that no two satellites will be affected within the same hour.

The second consideration is also dependent on solar-system geometry and is of importance to satellite systems whose spacecraft do not include a battery power supply which permits them to operate when the earth's shadow cuts off solar cell power for periods of up to 72 minutes a day around local midnight near the equinoxes. Operators of such systems may wish to position their satellites to the west of the western boundary of their service area so that this power failure will not occur until after local midnight.

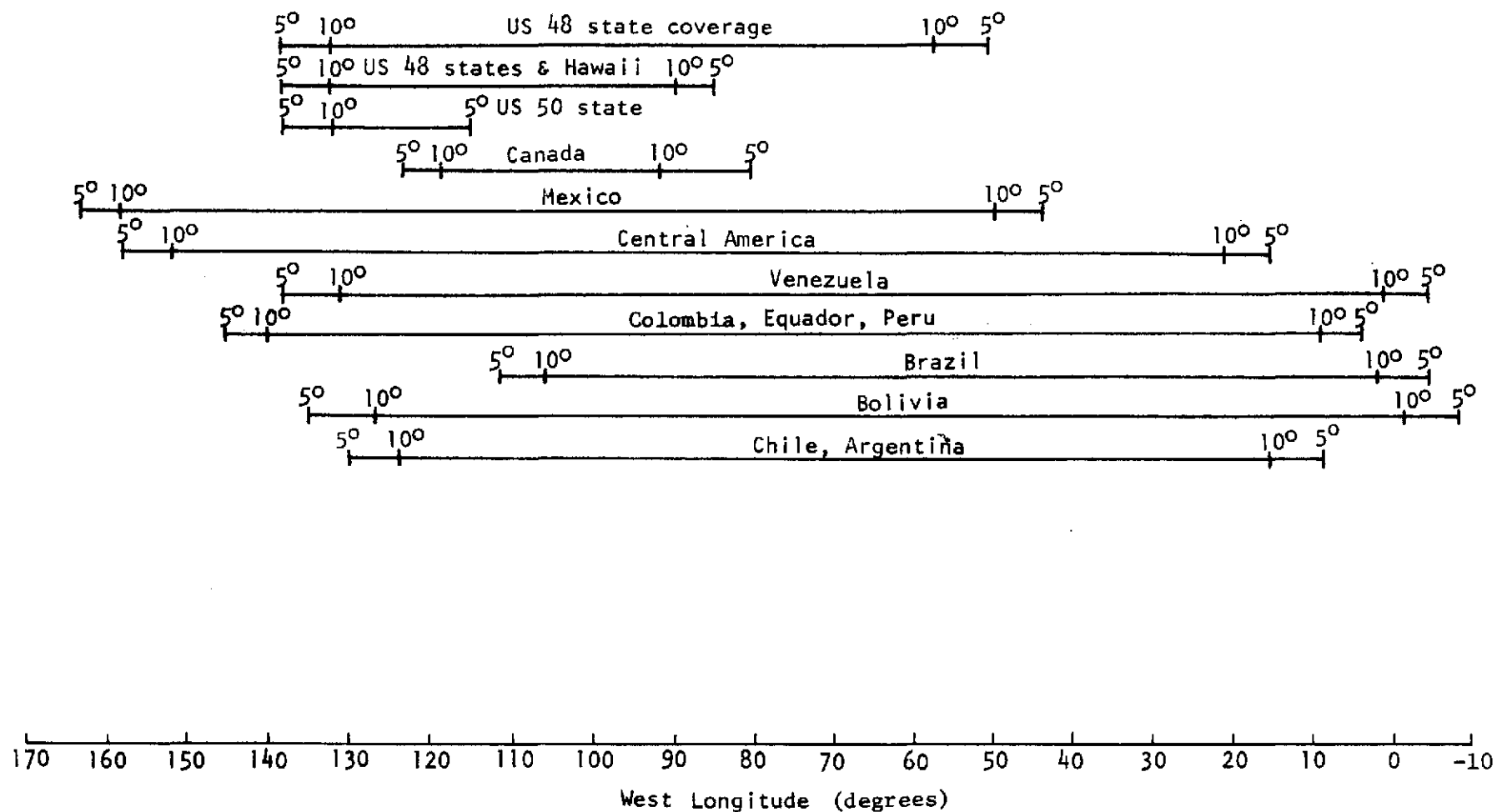


Fig. 1--Usable orbital arcs for various countries in ITU Region 2

Yet another consideration is of particular interest to planning for the broadcasting-satellite service. To keep ground receiving antenna costs low, most broadcasting-satellite systems contemplate using fixed antenna mounts; hence, all channels destined for a given group of receivers should be transmitted from the same orbital position.

Rf Links and Potential Demand in the Fixed-Satellite Service

As previously noted, a satellite communication system may be viewed as an aggregate of rf links, and an rf link may be viewed as an aggregate of message channels having the same terminal points. Thus, a description of the rf links likely to be needed in the fixed-satellite service can serve both as a summary of the anticipated communication needs to be met by the service and as a guide to the sorts of systems that might be built. As previously noted, the defining parameters of a link are those that describe its geometry, continuity, rf signal characteristics, and hardware.

Geometry. Since the 12 GHz band is restricted to domestic systems, the rf links in the fixed-satellite service of a nation can, in principle, connect only earth stations within the borders of that nation. The only fixed-satellite system so far proposed for the United States in this band⁽⁸⁾ envisioned high-capacity links between earth stations in 15 major cities in the contiguous states, plus additional stations in Hawaii and Alaska. The proposal also contemplated the provision of comparatively low-capacity links on demand between any two subscribers having the necessary earth-station installations.

A link in a fixed-satellite system usually involves only a single pair of earth stations, since all of the message channels on the associated carrier are intended for the same destination. However, a link may also be multidestinational--its carrier modulated by a multiplex of several groups of message channels, each group destined for a different earth station. In this case the entire carrier must be received and demodulated at each destination. Fixed-satellite links carrying telephone channels usually occur in oppositely directed pairs of the same capacity for obvious reasons, although the link from A to B need not utilize the same satellite as the link from B to A.

Continuity. Rf links in the fixed-satellite service may be either continuous or intermittent.* When there is a relatively continuous and constant amount of message traffic between a pair of earth stations, it is appropriate to establish continuous permanent or preassigned links between them. On the other hand, when traffic is intermittent or highly variable, more efficient use of satellite capacity is achieved by "demand assignment" of rf links. For this type of link, the bandwidth of a satellite transponder may be divided into a large number of comparatively narrow rf channels, which are assigned as needed to form rf links between pairs of earth stations. For example, in the Intelsat embodiment of this concept, called SPADE,⁽⁹⁻¹¹⁾ the 36 MHz bandwidth of a transponder is divided into 800 channels each 45 kHz wide, and each capable of carrying a single PCM (pulse code modulation) telephone channel on a PSK (phase-shift-keyed) carrier. To conserve transponder power, an assigned channel carries power only when the associated telephone user is actually speaking, making the link intermittent in a second sense.

Since any properly equipped pair of earth stations can at one time or another be assigned to any one of the 800 channels, the number of possible different intermittent links through the transponder is very large. For example, if there are 30 earth stations, the number of possible links is $800 \times 30 \times 29 = 696,000$.

There is of course a great deal of similarity among these links. Thus, the 1600 links corresponding to any one of the 435 possible earth-station pairs differ from each other only in carrier frequency or direction of transmission. Moreover, out of the grand total number of links, no more than 800 can be assigned at any one time and, because of voice actuation, fewer than half this number will be active simultaneously. Nevertheless, when analyzing interference to or from other systems using the 36 MHz of bandwidth assigned to the SPADE transponder, each of the 696,000 possible rf links should be considered.

Rf Signal Characteristics. The rf links of the 12 GHz domestic fixed-satellite systems can eventually be expected to provide all of the

* Deliberately intermittent, as opposed to the unintentional discontinuities provoked by propagation outages or equipment failure.

types of message channels offered by terrestrial common carriers and 4 GHz domestic satellites including single and multichannel transmission of teletype, telephony, data, facsimile, and video, plus distribution of high-quality television programming.

The characteristics of the rf signals on these links will of course depend on the number and type of message channels carried and on the parameters of the message processing, multiplexing, and modulation methods used. These combinations will in turn be influenced by the rf bandwidth to be used for satellite transponders and the amount of transponder output power backoff required to keep intermodulation at acceptably low levels when more than one carrier uses the same transponder.

Fixed satellites of both domestic and international systems designed for the 4 and 6 GHz band now use transponders with 36 MHz bandwidths. Each satellite uses the entire 500 MHz allocation--either for 12 transponders in nonoverlapping 40 MHz channels, or 24 transponders in overlapping channels (domestic systems only) such that the center frequency of one transponder lies in the guard band between adjacent transponders.

Typical signals in the domestic systems⁽¹²⁾ use the full transponder bandwidth for FM (frequency modulated) signals carrying a single television channel or several hundred telephone channels in FDM (frequency division multiplex). In the current international (Intelsat IV) system,⁽¹³⁾ rf signals range from a four-phase PSK carrier using a 45 kHz channel for a single PCM encoded telephone channel or an equivalent amount of digital data, through a sequence of FDM/FM signals with capacities from 24 to 972 telephone channels and bandwidths ranging from 2.5 to 25 MHz in steps of 2.5 MHz, to a 36 MHz FDM/FM signal carrying from 972 to 1872 telephone channels or one television channel with two associated sound channels. As with terrestrial fixed systems, the telephone channels may also be used individually or in groups to carry teletype, data, and facsimile at various rates.

Equipment Parameters. The sizes and types of transmitters, antennas, and receivers used for the rf links of fixed-satellite systems depend, as in any radio communication system, on a variety of technical, economic, operational, and environmental tradeoffs, which will be

elaborated upon in subsequent sections. The tradeoff of particular interest to sharing is between satellite eirp (equivalent isotropically radiated power) and earth-station sensitivity or figure-of-merit (ratio of receiving antenna gain to system noise temperature). The product of these two quantities for a given link must exceed a minimum value equal to the product of the link path loss (including fading margin) and the received carrier-to-noise temperature ratio required to yield the desired output message quality.

As the cost of an earth station is reduced by reducing the size of its antenna or by using a noisier receiver, thus lowering its figure-of-merit, the cost of the satellite will increase (if its capacity is to remain the same), since it must provide a proportionately higher eirp to that earth station. This might be a favorable trade in terms of total system cost as the number of earth stations becomes large (though not so favorable as for a broadcasting-satellite system where all earth receivers in the system are served by rf signals from the same satellite).

However, as the diameter of the earth-station antenna is decreased, its beamwidth increases and the spacing of satellites transmitting on the same frequency must be increased, thus reducing the potential capacity of the orbit and spectrum. Moreover, the accompanying increase in satellite eirp on that frequency will cause greater interference to co-channel receivers in other systems, causing a further reduction in orbit-spectrum utilization.

In the face of these tradeoffs, earth-station antenna sizes in the 12 GHz band can be expected to range between 10 and 32 ft. It is interesting to note that this corresponds closely in terms of gain and beamwidth to the range of 32 to 97 ft used in existing and planned 4 GHz domestic fixed-satellite systems.

Satellite eirps for an rf link using a given receiving-antenna size will then depend on the number of channels carried by the link. However, since the smaller earth stations will presumably serve users with smaller channel requirements and possibly lower message quality objectives, the variation in eirp per link will likely be much smaller than the 10:1 range in earth-station antenna gain (corresponding to the

3.2:1 range in antenna diameter). Based on the first proposal for a 12 GHz domsat system,⁽⁸⁾ the maximum eirp from a satellite transponder is likely to be on the order of 46 dBW.

Total Communication Needs. No attempt will be made to predict either the ultimate communication demands that 12 GHz fixed-satellite systems may be called upon to meet in various countries or the rate of growth of these demands. However, some indication of the future market potential in the United States can be obtained from the analysis of Booz-Allen and Hamilton, which was included with the 1971 domestic-satellite system application⁽⁸⁾ of the MCI Lockheed Satellite Corporation. For purposes of this analysis, the market was divided into the following seven major categories:

- o Leased private telephone circuits.
- o Leased data transmission circuits.
- o Leased low-speed message services.
- o CATV program distribution.
- o Electronic special delivery of mail.
- o TV/radio program distribution.
- o Common-carrier trunk lines.

The estimated total interstate circuit requirements (in equivalent 4 kHz duplex channels) are shown in Table 3. If it is assumed as in Ref. 8 that satellite systems can offer lower rates than terrestrial systems for distances over 1000 miles, and that approximately 20 percent of the total demand in all market categories is for such distances, then the total potential demand for satellite service would rise from about 90,000 equivalent 4 kHz duplex circuits in 1975 to 271,000 such circuits in 1985. Alternatively, if it is assumed that satellite systems would attract virtually all rather than only 20 percent of the market for electronic mail delivery, the foregoing total demands would increase to 100,000 circuits in 1975 and to 310,000 circuits in 1985.

In assessing these demand estimates, it must be borne in mind that the approximately twenty U.S. domestic satellites already planned for the 4 GHz band will have a total capacity (on a single channel per

Table 3

PROJECTED COMMUNICATION NEEDS

Demand Category	Required Capacity (Thousands of Duplex 4 kHz Circuits)		
	1975	1980	1985
Leased private-line voice	181	266	391
Leased data transmission ^a	22	40	87
Low-speed message transmission ^b	1.6	1.6	2
CATV distribution ^c	1.6	2.4	3.2
Electronic special delivery of mail ^d	12.4	24.4	48.4
TV/Radio program distribution ^c	9.6	9.6	10.8
Common-carrier trunk lines	220	423	813
Totals	448	767	1355
20% of totals	90	153	271

^a Assumes 12 low-speed data channels per telephone channel;
1 medium-speed data channel per telephone channel;
1/3 high-speed data channel per telephone channel.

^b Assumes 12 message-service channels per telephone channel.

^c Assumes 1 TV channel is equivalent to 800 simplex telephone channels.

^d Assumes 1 facsimile channel is equivalent to 3 telephone channels.

transponder basis) in the order of 150,000 equivalent duplex 4 kHz channels and thus might be expected to meet most of the projected demand through 1980.

Other surveys of communication needs that might be satisfied by future satellite systems have been conducted and/or analyzed.⁽¹⁴⁻¹⁶⁾ They provided a somewhat more detailed breakdown of estimated circuit requirements in certain categories and suggest higher demands in a few areas such as CATV distribution, but the overall total is of the same order of magnitude.

Rf Links and Potential Demand in the Broadcasting-Satellite Service

The links of broadcasting-satellite systems are likely to be much simpler than those of fixed-satellite systems in all defining characteristics.

Geometry. As with fixed-satellite links in the 12 GHz band, the rf links of a broadcasting-satellite system presumably will provide coverage only to regions within the country responsible for the system. In the United States, the first broadcasting-satellite links will probably provide community reception of educational television and medical teleconferencing to Alaska and Hawaii and to groups of states in the Rocky Mountain and Appalachian regions. These are the areas where rugged terrain, sparse population, and/or remoteness from program origination centers make video transmission by terrestrial facilities too expensive. In the first experimental U.S. systems, ^(17,18) non-simultaneous coverage to the different areas will be obtained for scheduled periods using one or two steerable, narrow (2.5 deg) satellite beams. Later systems can be expected to furnish simultaneous independent coverage with the aid of several separate beams but in most cases still from a single satellite.

In view of the extensive coverage provided by existing terrestrial television systems, augmented by cable television networks, it is not clear that a market will develop in the United States for broadcasting-satellite systems designed for individual or direct-to-the-home reception. If such systems should be developed, they very likely would be designed to provide separate coverage to each of the four U.S. time zones, and not necessarily from the same satellite. However, as noted in the discussion of the orbital resource, it is likely that only one satellite position will be used for each coverage area so as to eliminate a requirement for steerable antennas at the ground receivers.

Uplinks for feeding program material to both types of broadcasting satellites will probably be desired from at least one earth station in each coverage area and quite possibly from several properly equipped sites at points outside as well as within the coverage areas.

Continuity. Broadcasting-satellite links for community reception will probably not operate around the clock, and in the beginning, they might operate with a given geometry for only a few hours a day or only on certain scheduled days. Links for individual reception, on the other hand, might very well operate continuously, as do many terrestrial broadcasting links. But it is not in the nature of broadcast-

ing links to exhibit the kind of intermittency characterized by demand-assigned links in the fixed-satellite service.

Rf Signal Characteristics. The signals on the 12 GHz domestic broadcasting-satellite links of Region 2 countries will be modulated by 525-line National Television System Committee (NTSC) color or monochrome television pictures using frequency modulation to begin with, and perhaps using PSK modulation in the future when inexpensive digital decoders become available. In the case of the frequency-modulated signals, different rf bandwidths may be used to obtain the output signal quality in different systems. Since neither community nor individual broadcast reception requires as high output signal-to-noise ratios as are needed for program distribution in the fixed-satellite service, the optimum rf bandwidth in broadcasting-satellite systems will be smaller than in fixed-satellite systems.

Equipment Parameters. As with fixed-satellite links, once a value has been selected for the product of eirp and receiver figures-of-merit the broadcasting-satellite system tradeoff of greatest interest to sharing is between the factors in this product. A dominant consideration in determining the preferred values for these two parameters is the number of receiving terminals. This number ranges from hundreds or thousands for community reception to millions for individual reception and dictates the use of inexpensive receiving stations to prevent the ground segment cost from completely dominating the total system cost. Low-cost terminals imply smaller antenna sizes and higher receiver noise temperatures. Unless truly inexpensive automatic pointing and tracking systems are developed, it also precludes antennas for individual reception with beamwidths less than about 1 deg, and hence excludes effective antenna diameters greater than about 6 ft. For community reception, system cost optimization studies⁽¹⁹⁻²¹⁾ suggest a maximum diameter in the range from 7 to 20 ft depending on the number of receiving terminals.

Using detailed models of both satellites and receiving terminals, the cost-optimization studies found that the optimum satellite eirp per beam per channel varied from about 58 dBW for a system with a million

individual receivers using 7 ft antennas down to 44 dBW for a special community reception system with only 300 receiving terminals using 20 ft antennas. Between these extremes, educational TV systems having a few thousand terminals per beam had optimum eirps in the range from 48 to 51 dBW using receiving antenna diameters of about 12 ft.

Total Communication Needs. It is difficult to foretell the total demand for television channels that will materialize in the 12 GHz band. Estimates⁽¹⁴⁾ range from 3 to 12 channels for educational applications and up to 17 channels for biomedical network services. Again, it must be remembered that part of this demand will very likely be met in a lower frequency band--in this case, the 2500 to 2690 MHz band.

TECHNICAL APPROACH AND SIMPLIFYING ASSUMPTIONS

The straightforward approach used in this study to find preferred sharing strategies for the 12 GHz band involves these main steps:

1. Postulate baseline systems capable of meeting the range of communication needs anticipated in each of the two services.
2. Identify a number of compatible configurations of the baseline systems representing examples of different sharing strategies--i.e., various combinations of sharing tactics applied to different patterns of arranging the satellites in orbit.
3. Compare the sharing strategies identified in step 2 on the basis of relative orbit-spectrum utilization or utilization factor and the total communication capacities they permit.

Of these three steps, the second is by all odds the most challenging. To achieve good orbit-spectrum utilization with any strategy, it is necessary to use the same or overlapping radio-frequency channels on many different links. This, of course, leads to interlink interference, and it is a fundamental design objective that the effects of such interference on output message quality not exceed specified levels in any message channel of any system. It is in verifying the interference compatibility of the systems that the problem becomes challenging.

An extreme example will illustrate the problem. Using the equipment parameters mentioned in this section, a fixed satellite can easily have a capacity of over 19,000 simplex telephone channels (for example, it might use 24 interleaved transponders each carrying 800 channels). With a reasonable degree of coordination, identical satellites of this type can be spaced 0.5 deg apart, so that the 75 deg of orbital arc above 10 deg elevation angle in the contiguous United States could support a total of $151 \times 19,200 = 2.9 \times 10^6$ telephone channels. To be certain that the interference constraint is not violated, it would in principle be necessary to determine the interference in each of these channels. Considering that a given telephone channel is vulnerable to interference from all of the transmitters whose rf signals overlap the signal carrying the given channel (with frequency interleaving, there would be three overlapping signals), it follows that there will be $3 \times 150 = 450$ interference contributions to this channel from uplink transmissions and an equal number from downlinks. In principle, then, it would be necessary to compute, and appropriately add up, some $900 \times 2.9 \times 10^6 = 2.6 \times 10^9$ interference contributions.

In practice, of course, there are several ways to reduce the required computations to a more tractable level. One first chooses a "typical" reference rf channel and then, for each rf link using that channel, identifies the "worst" or "most-interfered-with" telephone channel on the corresponding carrier. With FDM basebands, the worst channel for both thermal noise and for interference is usually the highest-frequency channel.^(22,23) It is then necessary to compute only the interference contributions from the rf links whose carriers overlap those in the reference rf channel. In the example cited, this approach divides the number of interference contributions by a factor of $24 \times 800 = 19,200$.

For approximate parametric analysis, further reductions may be achieved by noting that the interference contributions from links involving satellites widely separated from the one supporting the given link are small. For a set of homogeneous links (links with the same signal and equipment parameters using equally spaced satellites), for example, the bulk of the interference to a

particular link will come from links employing either the same satellite or its two nearest neighbors on each side. In the example under discussion, this would divide the number of interference contributions by an additional factor of $\frac{151}{5} = 30$.

If the system configurations of interest to the 12 GHz sharing problem really were homogeneous or approximately so, it would not even be necessary to evaluate all of the links that use the reference rf channel. In a homogeneous system, these links differ in their interference performance primarily as a result of differences in the locations of the associated earth stations relative to the point at which the satellite antennas are aimed. It is thus possible to identify and confine the calculations to the link or links that can be expected to suffer the greatest interference. Indeed, by taking advantage of the homogeneity of signal and equipment parameters and the regularity of satellite spacing, the interference performance of the worst telephone channel on the worst rf link can be expressed in the form of an equation applicable to a wide range of link parameters and satellite spacings.

Such a parametric approach is invaluable in gaining insight into the impact of various sharing tactics and in the development of sharing strategies for the far-from-homogeneous combinations of 12 GHz fixed-satellite and broadcasting-satellite systems that can be anticipated. However, to evaluate the interference compatibility of these more relevant configurations of inhomogeneous links, involving a variety of different rf channel widths as well as inhomogeneities in signal and equipment parameters, numerical evaluation and summation of thousands of interference contributions appears to be inevitable and the use of an appropriate computer simulation program is clearly indicated.

That is the approach followed in this report. Parametric evaluations of homogeneous systems and of the interfaces between two or more such systems are used as a guide in the design of promising sharing strategies for selected reference or baseline systems. These strategies are then tested for interference compatibility using a specially developed computer model that is described in the Appendix.

To keep the number of types of links to be considered in the model to a reasonable level, it is assumed that all links employ frequency modulation. It was felt that this assumption was not unduly restrictive, because it is likely that first-generation systems in both satellite services will in fact use frequency modulation and second, studies of orbit-spectrum utilization with different modulation methods^(22,24-26) suggest that FM is quite comparable to the most frequently considered alternative, four-level PSK.

A number of other standard simplifying assumptions, such as the use of sidelobe envelopes to represent antenna patterns, and a restriction to perfectly geostationary satellites, are described in detail at appropriate points in the report.

III. NOISE PERFORMANCE AND BASELINE SYSTEMS

The fundamental performance objective to be met in designing the rf links of a radio communication system describes the maximum permissible noise in the message channels carried by the links. Taken in conjunction with data on the propagation characteristics of the link, the noise objective determines the allowable combinations of signal and equipment parameters.

In this section, equations describing the relationship of the various link parameters to noise performance for fixed- and broadcasting-satellite links are given first. The applicable message noise objectives are described next and compared with propagation statistics for the 12 GHz band. Finally, a number of hypothetical reference or baseline links appropriate to the fixed- and broadcasting-satellite services are postulated for subsequent use in evaluating sharing tactics and strategies for these services.

NOISE PERFORMANCE EQUATIONS

As explained in the preceding section, the emphasis in this report is on analog messages such as telephone and television signals. The effect of noise on the quality of these signals is normally expressed in terms of the signal-to-noise ratio at the message channel output. This ratio may be defined in various ways for each type of message, but in all cases it can be related to the carrier-to-rf noise ratios at the inputs to the satellite transponder and the earth-station receiver through which the carrier passes.

Multichannel Telephony

On most present-day satellite links, telephone channels are first combined into multichannel basebands using frequency division multiplexing and the baseband is then used to frequency modulate the carrier.

In the signal-to-noise (S/N) ratio at the output of a given telephone channel, S is the power of a reference signal representing a

speaker--e.g., a sinusoidal test tone--and N is the noise power, after psophometric weighting to account for the frequency response of the human ear.

The relationship between S/N and the effective carrier-to-noise ratio $(C/N)'$ on the rf link is a simple proportionality providing only that $(C/N)'$ exceeds the FM improvement threshold. Thus,

$$S/N = R(C/N)'$$

where the proportionality factor R is called the receiver transfer characteristic, and $(C/N)'$ is given by the reciprocal of the sum of the reciprocal apparent carrier-to-noise ratios at the uplink and downlink receiver input.⁽²⁷⁾

$$(C/N)' = \left[(C/N)_{up}^{-1} + (C/N)_{down}^{-1} \right]^{-1}$$

Combining the two equations, the output noise-to-signal ratio is

$$N/S = \frac{1}{R} \left[(N/C)_{up} + (N/C)_{down} \right] \quad (1)$$

An equivalent and more commonly used measure of telephone signal quality is the noise power in pWOp (picowatts at a point of zero relative level, psophometrically weighted). At such a point, the signal is, by definition, a sinusoidal test tone with a power $1 \text{ mW} = 10^9 \text{ pW}$, so by Eq. (1), the total noise at the channel output

$$N = N_{up} + N_{down} \quad (2)$$

where

$$\left. \begin{aligned} N_{up} &= 10^9 (N/C)_{up}/R \\ N_{down} &= 10^9 (N/C)_{down}/R \end{aligned} \right\} \quad (3)$$

are, respectively, the uplink and downlink noise contributions to the channel.

It is apparent that determination of the noise performance of a telephone channel on an rf link reduces to computation of the receiver transfer characteristic (RTC) for the channel and the uplink and downlink carrier-to-noise ratios. The former depends on the rf signal parameters and the latter on the equipment parameters of the link.

For the noisiest (highest frequency) telephone channel on a pre-emphasized FDM/FM signal, corrupted by white gaussian noise, the RTC is given by^(22,27)

$$R = R_{FN} = m^2 \frac{W}{f_m} w_n w_p f(n) \quad (4)$$

where the subscripts F and N, respectively, indicate the types of wanted and unwanted signal, and

m = rms modulation index

W = rf bandwidth

f_m = maximum baseband frequency

w_n = psophometric noise weighting factor ($10 \log w_n = 2.5$ dB)

w_p = preemphasis improvement factor ($10 \log w_p = 4$ dB)

$$f(n) = \frac{f_m}{bg^2(n)} = \begin{cases} 1.71 n^{0.6}, & 12 \leq n < 240 \\ 42.8, & n \geq 240 \end{cases} \quad (5)$$

n = number of telephone channels in FDM baseband

$g(n)$ = ratio of rms frequency deviation of n channel baseband signal to that of single channel test tone

b = highest frequency in telephone signal ($b = 3.1$ kHz)

In the equation for $f(n)$ it was assumed that for satellite basebands, the highest baseband frequency in MHz is approximated by

$$f_m = 0.0042 n \quad (6)$$

and that the ratio of frequency deviations $g(n)$ is given by the International Radio Consultative Committee (CCIR) load factor

$$20 \log g(n) = \begin{cases} -1 + 4 \log n, & 12 \leq n < 240 \\ -15 + 10 \log n, & n \geq 240 \end{cases}$$

which may also be interpreted as the baseband power in dBm at a point of zero relative level.

Finally, it will be assumed that the rf bandwidth W is given by Carson's rule

$$W = 2f_m (\sqrt{\Lambda} m + 1) \quad (7)$$

where

Λ = baseband peak-to-average power ratio

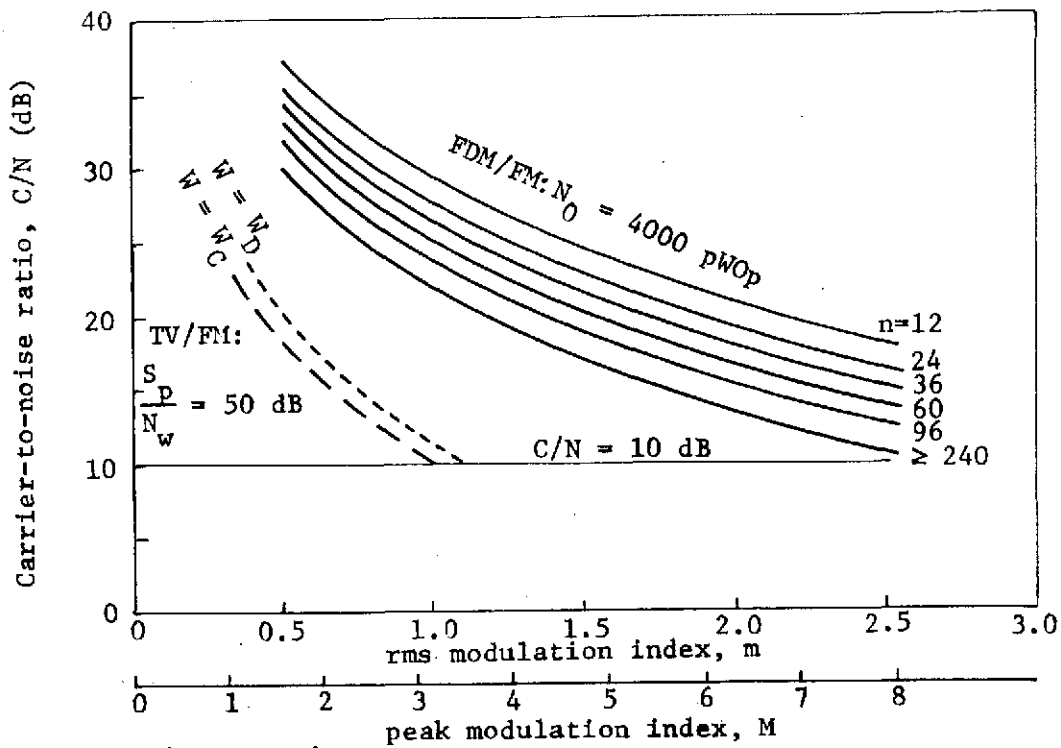
For FDM basebands, Λ will be set equal to 10, since the amplitude distribution of an FDM baseband is approximately gaussian for $n \geq 12$.

Combining Eqs. (3) and (4), and expressing the result in dB, the carrier-to-noise ratio corresponding to a thermal-noise contribution of N_o pWOp in the worst telephone channel of an n channel baseband with rms modulation index m is given by

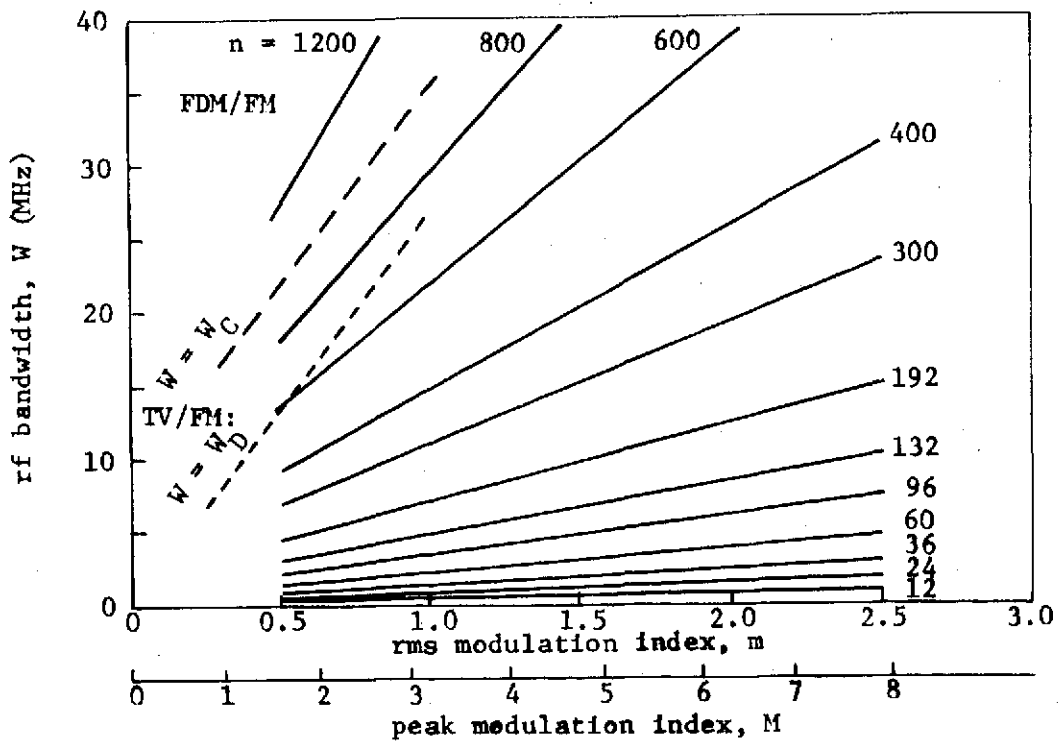
$$10 \log (C/N)_o = 64.2 - 10 \log N_o - 10 \log m^2 (\sqrt{\Lambda} m + 1) + \begin{cases} 14 - 6 \log n, & 12 \leq n \leq 240 \\ 0, & n > 240 \end{cases} \quad (8)$$

This equation may be applied to either the uplink or downlink portion of an rf link.

Plots of Eq. (8) are shown in Fig. 2a for various numbers of channels and an output noise contribution $N_o = 4000$ pWOp; this is purely a reference value. For a different noise objective N_1 the curves would all shift upward by $10 \log N_o/N_1$ dB. It is apparent from the figure that for a given number of telephone channels, the required C/N decreases significantly as the modulation index m is increased. It is also apparent that there is a maximum modulation



a. Carrier-to-noise



b. RF bandwidth

Fig. 2--Carrier-to-noise and rf bandwidth requirements for preemphasized FDM/FM and TV/FM links

index m_{\max} beyond which C/N would drop below threshold. If threshold is taken as 10 dB, for example, $m_{\max} = 2.6$ for $n \geq 240$ and $N_o = 4000$ pWOp. The corresponding threshold value of carrier power is also the minimum that will yield this noise performance.

Values of m greater than m_{\max} can be used providing C/N is kept at or above threshold, but the associated carrier power will be greater than for $m = m_{\max}$ and the output noise will be proportionately lower than 4000 pWOp. In practice, a value of modulation index less than m_{\max} is normally chosen so that the associated C/N exceeds threshold by a fading margin that ensures above-threshold operation for all but a small fraction of the time, despite transient increases in propagation losses, as well as antenna misalignment, tube decay, etc.

For example, if the required fading margin is 10 dB, reference to Fig. 2a shows that the maximum modulation index for $n \geq 240$ and $N_o = 4000$ pWOp is 1.16. Operation at this modulation index will require the smallest carrier power for the specified noise objective and fading margin. As a result, such a choice of modulation index is appropriate to the usual case where satellite power is limited. Output noise will increase above 4000 pWOp during a fade, but, as will be seen, these increases are usually permitted by the noise-performance objectives. The main consideration is that circuit outages caused by below-threshold operation be held either to specified small fractions of the time or to some specified maximum durations.

Operation at still lower values of modulation index is also possible, albeit at a greater cost in carrier power. The increase in power is less than the increase in required carrier-to-noise ratio, however, because for a given number of channels, the rf bandwidth and hence the rf noise decreases linearly with m . Indeed, it is the bandwidth savings that motivate low index operation despite the higher cost in power. Such operation is sometimes described as "bandwidth limited" to distinguish it from operation at the maximum modulation index (for the required margin) which is called "power limited."

The dependence of rf bandwidth on modulation index for various numbers of telephone channels, n , is given by Eqs. (6) and (7) and is plotted in Fig. 2b. Using Figs. 2a and 2b together, the cost in power

and the savings in bandwidth of operating at less than the maximum modulation index for a specified fading margin may be determined. It has been noted that if $n \geq 240$, the maximum modulation index for a 10 dB fading margin is 1.16. From Fig. 2b, the corresponding value of W is about 39.2 n kHz. If the modulation index is reduced to 0.5, the bandwidth is reduced by a factor of 0.59 to 21.7 n kHz, which reduces the rf noise in this bandwidth by 2.6 dB. At the same time, Fig. 2a shows that the required C/N has increased from 20 dB to 29.8 dB, so that carrier power must be increased by a net of 7.2 dB. The noise performance in the absence of fading is still 4000 pWOp, but the margin above threshold is now 19.8 dB rather than 10 dB.

The tradeoff between power and bandwidth may be put in another form, which is both more useful in system planning and which displays the power savings more directly by referring carrier power to the noise in a fixed bandwidth rather than in the rf bandwidth. For this purpose, the received carrier power C is expressed in terms of the parameters of the transmitting and receiving equipment and of the propagation path. If, for the path of interest (uplink or downlink), E is the eirp of the transmitter in the direction of the receiver, and G is the gain of the receiving antenna in the direction of the transmitter, then from the definition of path loss L , the received carrier power is

$$C = EG/L \quad (9)$$

Hence, the product of eirp and the receiver figure-of-merit G/T may be written

$$EG/T = LC/T = LkWC/N \quad (10)$$

where

T = receiving system noise temperature

k = Boltzmann's constant ($1.38 \times 10^{-23} \text{ J/}^\circ\text{K}$)

W = rf bandwidth

$N = kWT$ = noise power in rf bandwidth

Expressing this equation in dB and substituting from Eqs. (7) and (8),

$$10 \log \left(E \frac{G}{T} \right)_0 = 10 \log L - 115.2 - 10 \log N_o - 20 \log \left(\frac{W}{.0084n} - 1 \right) + \begin{cases} 14 + 4 \log n, & 12 \leq n < 240 \\ 10 \log n, & n \geq 240 \end{cases} \quad (11)$$

where, as before, W is the rf bandwidth in MHz and N_o is the noise power in pWOp to be allowed in the worst telephone channel. Given the desired value of N_o , and the path loss in dB, this equation gives directly in terms of W and n , the required product of eirp and figure-of-merit.

Plots of EG/T versus W for FDM/FM basebands ranging from 12 to 1200 channels are given in Fig. 3 using Eq. (11) with $N_o = 4000$ pWOp and $L = 206$ dB, the approximate path loss at 12 GHz including clear atmospheric attenuation for a typical path. Also plotted is a line showing the values of EG/T corresponding to a 10 dB FM threshold.

Figure 3 may be used in a variety of ways to design an rf link, or to determine the noise performance of a given link. As an example of the latter, suppose a 36 MHz satellite transponder has an eirp of 40 dBW in the direction of an earth station with a G/T of 34 dB/°K (e.g., a 32 ft antenna feeding a 300 deg receiver) and is used to transmit an 800 channel FDM/FM carrier. The resultant system margin of this downlink relative to a noise-performance objective of 4000 pWOp and relative to the FM threshold may then be found by locating the point in Fig. 3 corresponding to $W = 36$ MHz and $EG/T = 74$ dB. It is seen that the margins in question are 3 dB and 11 dB, respectively.

The same curves may be used for uplink calculations, with proper adjustments to account for the normally lower noise objective (about 6 dB) and higher path loss (about 1.5 dB). In all cases, however, it should be remembered that the values of E and of G in the product EG/T are to be taken in the directions along the path; they are not necessarily the maximum or on-axis values.

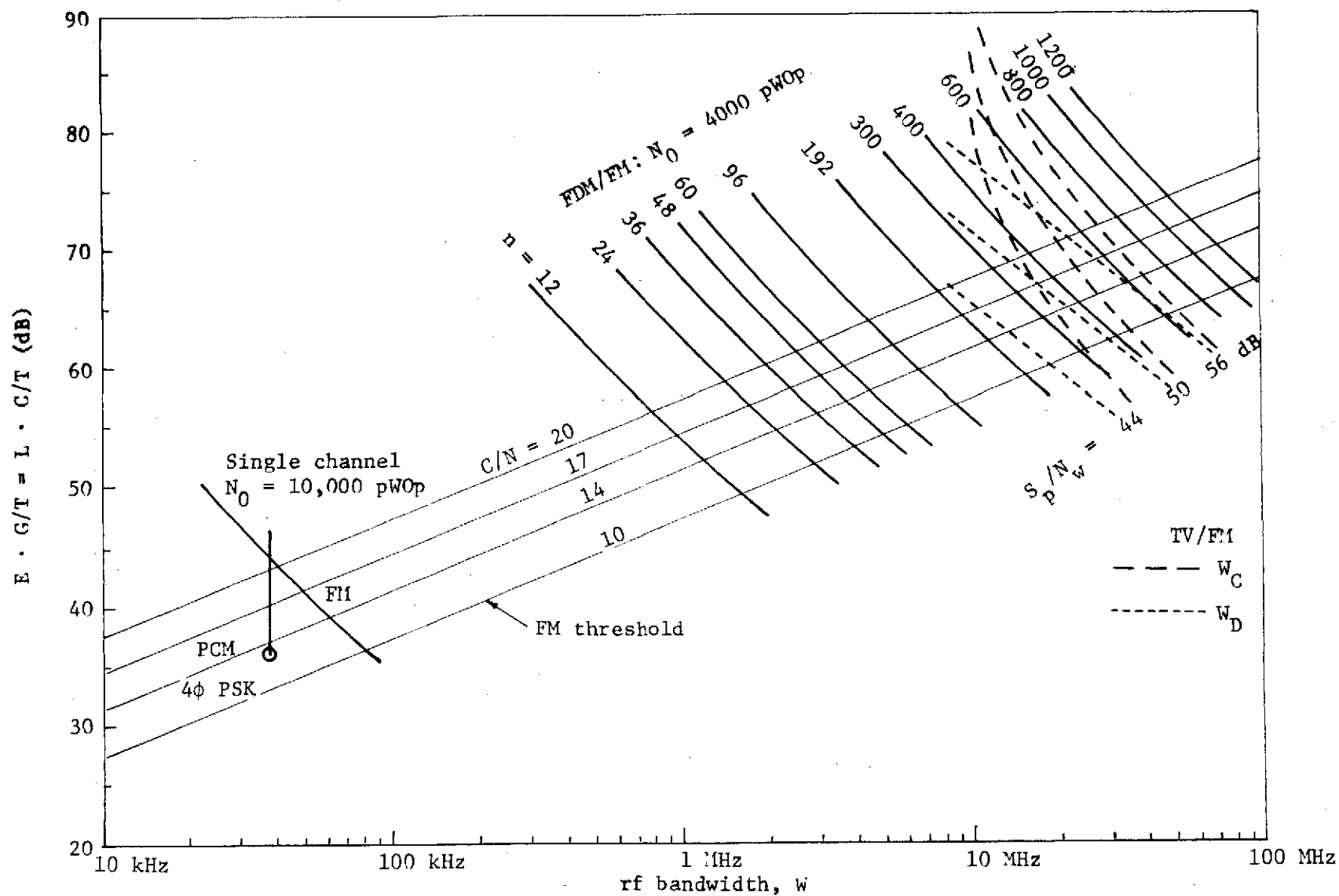


Fig. 3--Power-bandwidth tradeoffs for preemphasized FDM/FM and TV/FM links

Single-Channel-per-Carrier Telephony

All of the preceding equations apply to carriers frequency modulated by multichannel telephone basebands. Although it is expected that such FDM/FM links will continue to be used for heavy and medium traffic links, there appears to be an increasing need for links whose carriers are modulated by a single telephone or data channel.

The speech waveform in a telephone channel is by no means a simple modulating signal. Its structure is characterized by frequent periods of silence ranging in length from fractions of a second to minutes and by an extremely wide dynamic range in amplitude. Even discounting the silent periods, the ratio of peak-to-rms amplitude is quite large, and the rms amplitude itself can vary widely from talker to talker.

One successful approach to the efficient transmission of speech first processes and encodes the telephone signal using PCM and then applies the resultant digital stream to a carrier using 4-phase PSK. (9-11) To display the EG/T product and rf bandwidth required for such transmission on the graph of Fig. 3, it is necessary to estimate the equivalent test-tone-to-noise ratio of the demodulated, decoded, deprocessed speech signal as a function of the bit error rate p_e of the digital transmission and the number of bits k per PCM sample, and to estimate the threshold carrier-to-noise ratio for the required value of p_e .

The circle shown at 38 kHz in Fig. 3 corresponds to threshold operation with a 13 dB carrier-to-noise ratio yielding $p_e = 10^{-4}$ which is appropriate for the quantizing "test-tone-to-noise ratio" of about 50 dB corresponding to 7-bit PCM. However, it should be noted that published equations^(22,27,28) for the dependence of the equivalent test-tone-to-noise ratio on the number of bits per PCM sample vary over a range of 8 dB depending on the speech processing assumed. It is also not clear that the same weighting factor applies to both quantizing and thermal noise. In any case, the vertical line proceeding upward from the circle indicates the values of EG/T that would be used to maintain an appropriate fading margin.

As an alternative for comparison with single-channel-per-carrier PCM/PSK, the EG/T versus W curve for single-channel FM is also shown in Fig. 3. The curve is based on an extrapolation of a study of voice

communication techniques for aeronautical and marine applications⁽²⁸⁾ conducted at COMSAT Laboratories. For a given margin above their respective thresholds, single-channel FM appears to offer power savings which increase with the size of the required fading margin but at the cost of greater rf bandwidth until a margin of 11 dB is reached. For a margin higher than this, FM is less costly in both power and bandwidth. Moreover, the quality of the FM channel increases with margin whereas the PCM channel does not.

Television Channels

The objective measure normally used to express the quality of a television picture degraded only by thermal noise is the ratio of the peak-to-peak picture or luminance signal amplitude (the video signal excluding synchronizing pulses)-to-weighted rms noise, which will be written as a power ratio, S_p/N_w . Its dependence on the uplink and downlink carrier-to-noise ratios is given by an equation similar to Eq. (1)

$$N_w/S_p = (N/C) \cdot R = \frac{1}{R} \left[(N/C)_{up} + (N/C)_{down} \right] \quad (12)$$

where, assuming the use of frequency modulation, the receiver transfer characteristic is given by^(22,27)

$$R = R_{TN} = 6 M^2 w_N w_P W/f_v \quad (13)$$

and

M = (peak) modulation index

f_v = highest modulating frequency in video baseband

W = rf bandwidth

w_N = noise weighting factor

w_P = preemphasis improvement factor

In terms of the peak-to-peak frequency deviation (including synchronizing pulses), Δf_{pp} ,

$$M = \frac{1}{2} \Delta f_{pp} / f_v \quad (14)$$

Most current rf link designs set W equal to the Carson's-rule bandwidth

$$W_C = \Delta f_{pp} + 2 f_v = 2 f_v (M + 1) \quad (15)$$

but recent experimental measurements^{(19)*} indicate that preemphasized television signals can use rf bandwidths equal to or less than Δf_{pp} without exceeding CCIR distortion objectives.⁽²⁹⁾ To assess the implications on the power-bandwidth tradeoff of using an rf bandwidth equal to the peak-to-peak deviation, we will denote Δf_{pp} as the "deviation bandwidth"

$$W_D = \Delta f_{pp} = 2 f_v M \quad (16)$$

Combining Eqs. (15) and (16) with Eq. (13),

$$R_{TN} = \begin{cases} 12 w_N w_P M^2 (M + 1), & W = W_C \\ 12 w_N w_P M^3, & W = W_D \end{cases} \quad (17)$$

In the foregoing equations, the values of f_v and $w_N w_P$ for a pre-emphasized 525-line television baseband are

$$f_v = 4.2 \text{ MHz}, \quad 10 \log (w_N w_P) = 12.8 \text{ dB} \quad (18)$$

* Hodge, William H., *Frequency Modulation Television Analysis*, Vol. 1, *Threshold Impulse Analysis*, Computer Sciences Corporation, CSC Report 3007-1, 26 November 1973; and William H. Hodge and Wing H. Wong, *Frequency Modulation Television Analysis*, Vol. 2, *Distortion Analysis*, Computer Sciences Corporation, CSC Report 3007-2, 26 November 1973.

Substituting from Eqs. (17) and (18) into Eq. (12), it follows that the equivalent carrier-to-noise ratio required to yield an output picture signal-to-noise ratio $(S_p/N_w)_o$ is given by

$$10 \log (C/N)_o = 10 \log (S_p/N_w)_o - 23.6 - \begin{cases} 10 \log M^2(M+1), & W = W_C \\ 30 \log M, & W = W_D \end{cases} \quad (19)$$

This relationship may be applied to the rf link as a whole or to the uplinks and downlinks separately. In the former case $(C/N)_o$ is the primed equivalent carrier-to-noise ratio of Eq. (12) and $(S_p/N_w)_o$ represents the actual noise performance obtained. In the latter case, $(C/N)_o$ represents the apparent carrier-to-noise ratio, $(C/N)_{up}$ or $(C/N)_{down}$ in Eq. (12), and $(S_p/N_w)_o$ represents the ratio of picture-signal-to-weighted uplink or downlink noise contribution, respectively. The various output signal-to-noise ratios are related to each other in the same fashion as the corresponding carrier-to-noise ratios.

$$N_w/S_p = (N_w/S_p)_{up} + (N_w/S_p)_{down}$$

A plot of Eq. (19) is given in Fig. 2a for a reference downlink noise objective $(S_p/N_w)_o = 50$ dB. The corresponding bandwidth requirements are shown in Fig. 2b. The relation between the scales for peak and rms modulation index is established by the assumption that the peak-to-average power ratio for an FDM/FM baseband signal is 10 dB. The rms modulation scale should only be used in connection with such telephony signals; it is not to be inferred that the same peak-to-average ratio applies to a television baseband.

An inspection of the television curves in Fig. 2 leads to several observations. For a given modulation index or peak-to-peak frequency deviation, use of the deviation bandwidth W_D rather than the Carson bandwidth results in a 1 to 3 dB higher carrier-to-noise ratio. But when using different modulation indices so as to operate in the same rf bandwidth, use of the deviation bandwidth requires from 2 to 6 dB less carrier

power. Conversely, when operated with the same carrier power, use of the deviation bandwidth results in a bandwidth reduction of from 25 to 55 percent compared with use of the Carson bandwidth, and at the same time affords an additional margin above threshold of from 1 to 3 dB.

Comparing a 1000-channel FDM/FM carrier with a TV/FM signal having the same peak modulation index, and hence the same Carson bandwidth (since the baseband bandwidths are the same), the carrier power required for a worst-channel noise of 4000 pWOp with the FDM baseband will yield a 62 dB output signal-to-noise ratio with the TV signal.

Of greater interest, however, are the more direct comparisons that can be made when the EG/T requirements for television transmission are plotted. The equation for this purpose, which may be obtained from Eq. (19) in the same way that Eq. (11) was obtained from Eq. (8), is

$$10 \log (EG/T)_o = 10 \log L - 183 + 10 \log (S_p/N_w)_o - \begin{cases} 20 \log (W/8.4 - 1), & W = W_C \\ 20 \log (W/8.4), & W = W_D \end{cases} \quad (20)$$

Setting $L = 206$ dB as before, the results for $(S_p/N_w)_o = 44, 50,$ and 56 dB are shown in Fig. 3.

Comparing the TV curves with each other confirms the previous conclusion that use of the deviation rather than the Carson bandwidth saves from 2 to 6 dB in power (depending on the required fading margin) for the same total rf bandwidth.

Comparing the TV/FM curves with the FDM/FM curves, it is seen that when the Carson bandwidth is used, the EG/T versus rf bandwidth tradeoff for the downlink signal-to-noise objective of 50 dB is comparable to that for a 500 channel carrier with 4000 pWOp of downlink noise in the worst channel. For a 62 dB TV signal the tradeoff curve is identical to that for a 1000 channel carrier.

When the deviation bandwidth is used, however, the equivalent FDM/FM carrier has a capacity of between 300 and 400 channels

(depending on fading margin) for a 50 dB downlink TV signal-to-noise objective, and about 800 channels for a 62 dB downlink objective.

MESSAGE OBJECTIVES

As just explained, the allowable combinations of EG/T and rf bandwidth W for an rf link are determined by the message noise objectives and the required fading margin. The noise objectives will be discussed first.

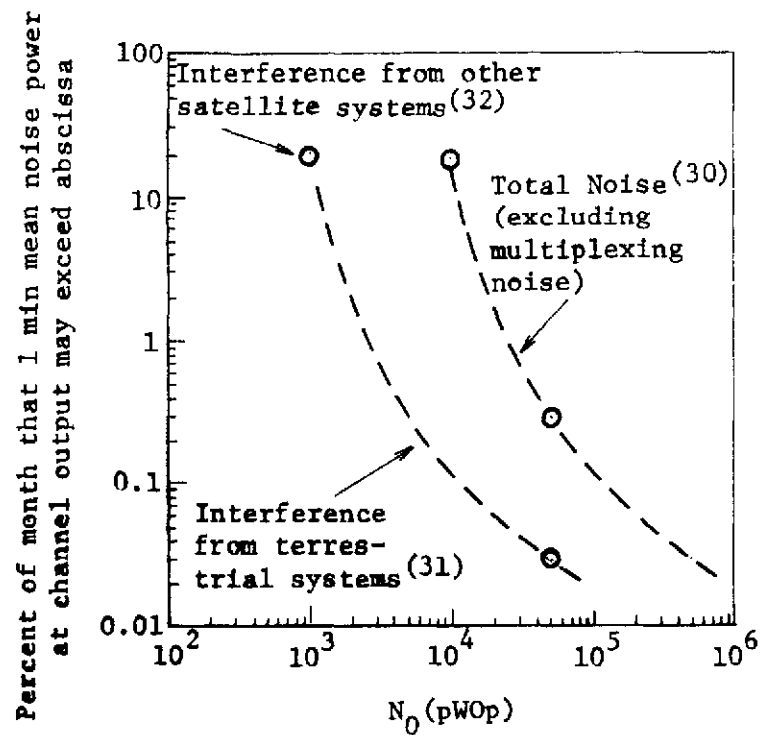
Telephone Channels

The CCIR objectives for telephone⁽³⁰⁻³²⁾ channels in fixed-satellite systems are expressed in terms of the values of noise power in pWOp that can be exceeded for various percentages of the time. Limits are placed only on the total noise from all sources (except multiplexing equipment) and on the amount of that noise that can be caused by interference from terrestrial systems and from other satellite systems.

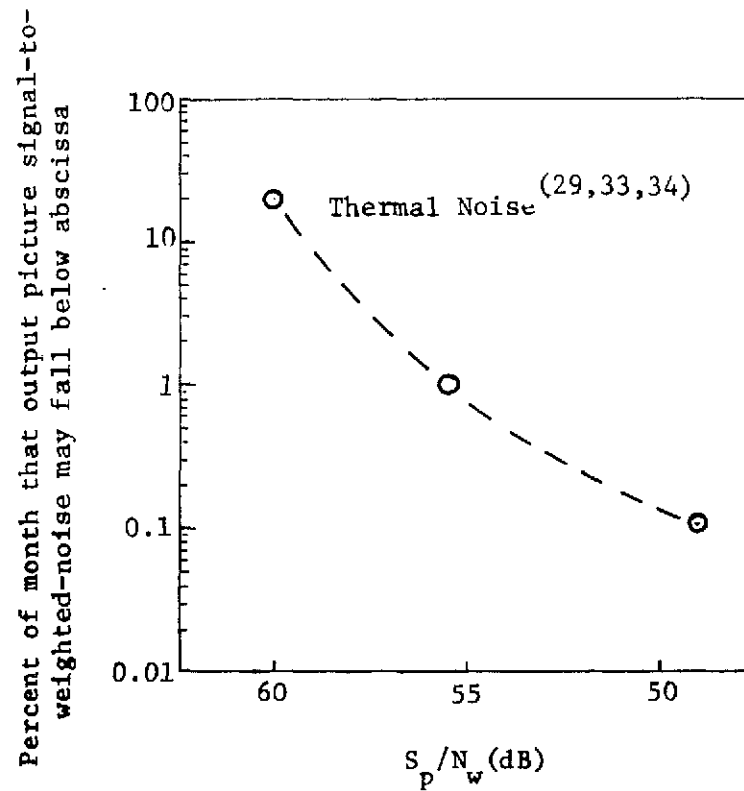
More specifically, limits are placed on the total and interference noise powers averaged over 1-minute intervals as shown in Fig. 4a. In addition, the limits of 10,000 and 100 pWOp which the 1-minute mean total and interference powers cannot exceed for more than 20 percent of any month, are also to be applied to the psophometrically weighted mean noise power in any hour. Finally, the essentially instantaneous (integrating time of 5 ms) unweighted total noise power is not to exceed 1,000,000 pWOp for more than 0.003 percent of the time.

The partition of the total noise allowance among sources other than interference, such as uplink and downlink thermal noise, intermodulation noise, and various kinds of equipment noise, is left to the system designer. The CCIR also does not specify the limits on noise for percentages of time other than those given; the dashed curves in Fig. 4a represent only one possible interpretation of the maximum permissible fading. Link design should be based on measured fading statistics for the link in question and should ensure that the noise objectives are met for each of the specified percentages of time.

As a basis for the reference systems considered in this report, the following noise partition will be adopted for unfaded (clear-sky)



a. FDM telephone channels



b. 525-line TV channels

Fig. 4--CCIR noise and interference objectives

operation when two or more carriers use the same transponder.

Uplink thermal noise	1,000 pWOp
Downlink thermal noise	4,000
Satellite intermodulation noise	1,500
Earth-station intermodulation and equipment noise	1,500
Interference from terrestrial systems	1,000
Interference from other satellite systems	<u>1,000</u>
	10,000 pWOp

This partition is consistent with the noise budget used in planning the Intelsat IV system,⁽¹³⁾ and differs but little from that discussed in the NASA analysis of the orbit and spectrum compatibility of proposed 4 GHz domestic systems.⁽¹²⁾ It should be noted in this connection that, so long as the interference noise allowance is fixed, the particular objectives adopted for thermal noise can be expected to have only a small and indirect effect on sharing considerations.

Television Channels

The CCIR recommendation for the permissible random noise at the output of a fixed-satellite link carrying a television channel⁽³³⁾ is the same as for a 2500 km hypothetical reference circuit in a terrestrial radio relay system. The provisional terrestrial noise objectives^(29,34) for 525-line television systems in the United States and Canada are shown in Fig. 4b.

As with the telephone noise objectives, the percentages of time cited apply to the worst month. Moreover, the television objective varies with percentage of the time in almost exactly the same way as does the telephone objective; for example, the difference between the 20 percent level and the 0.1 percent level is about 12 dB in both cases. Thus, if the actual fading is less severe than one objective, it will also be so for the other.

Strictly speaking, fixed-satellite circuits are not required to meet the terrestrial 20 percent signal-to-noise objective of 60 dB, and it would appear that in practice, levels in the order of 53 dB are acceptable for unfaded international satellite circuits⁽¹³⁾ in the 4 GHz band. The 12 GHz baseline fixed-satellite systems considered in this report will be designed to provide an output signal-to-weighted noise ratio exceeding 55 dB for all but 1 percent of the time.

No official recommendation exists for broadcasting-satellite signal-to-noise objectives, but it seems reasonable to require 49 dB for community reception and 43 dB for individual reception, each level to be exceeded for all but 1 percent of the time.

FADING STATISTICS

The signal fading statistics on the up and down paths of the rf links determine the fractions of time that the received carrier power and hence the output channel noise will spend at various levels relative to their clear-sky or unfaded values. If these statistics are less severe than those implied by the message objectives, link designs can be based on the clear-sky noise budget and the message objectives will automatically be met so long as the carrier-to-noise ratio remains above threshold.

At 12 and 14 GHz, the principal cause of fading is attenuation by rainfall. Although a considerable amount of data has been collected using both radiometric techniques and direct measurements on satellite-earth paths, there remains considerable uncertainty about the fading allowance to be applied on a particular path, especially for small percentages of the time. Probably the most authoritative and relevant statistics are those assembled by Ippolito⁽³⁵⁾ for 15.3 GHz paths, and summarized in Fig. 5 for five U.S. receiving sites. These fading distributions have been extrapolated to 12 GHz using data developed in a recent Rand report⁽³⁶⁾ and the results plotted with solid lines in Fig. 6.

A rather different result,⁽³⁷⁾ presumably extrapolated from data on paths in the eastern United States similar to those shown in Fig. 5, is given by the dashed curve labeled "no diversity" in Fig. 6. This

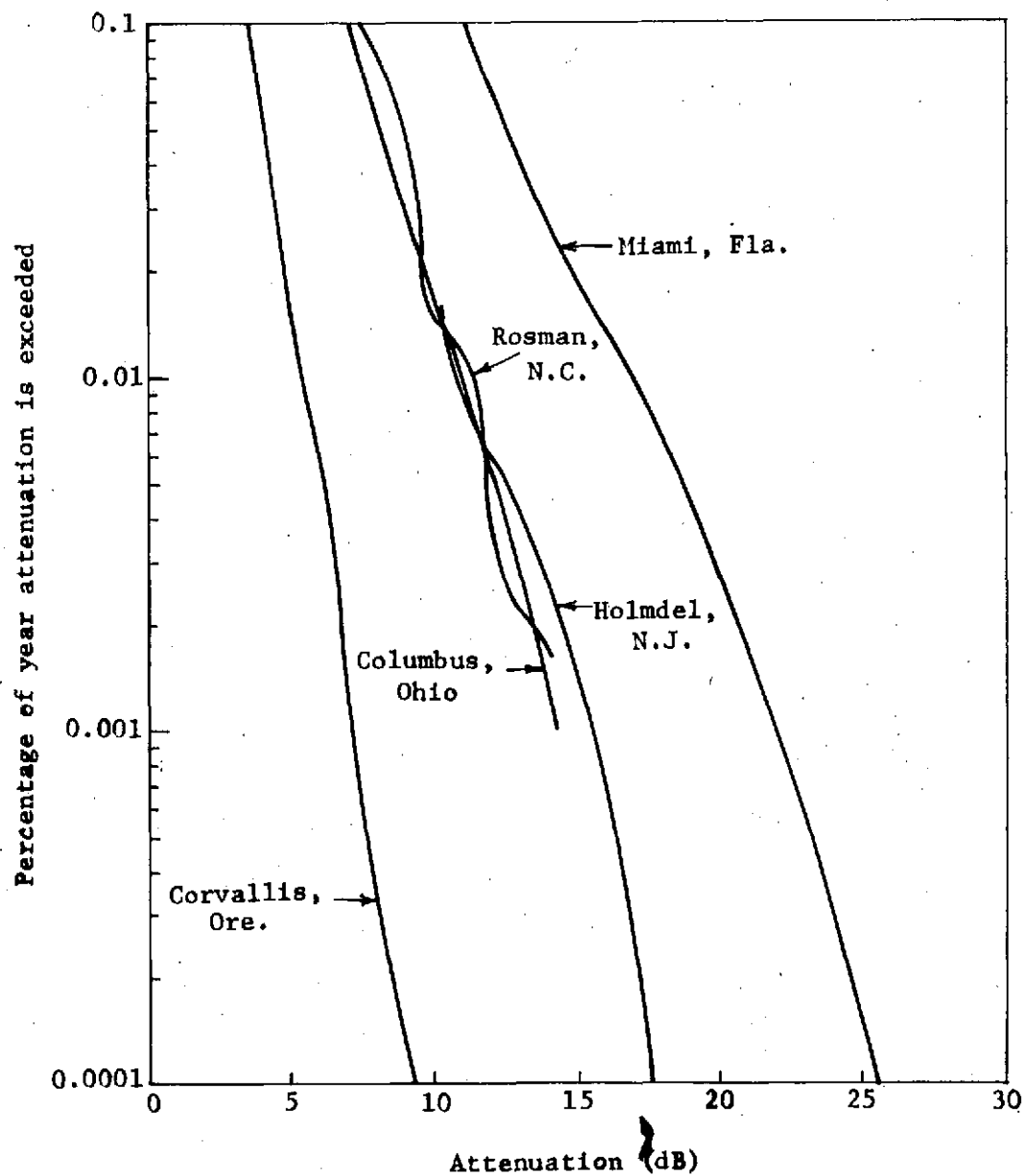


Fig. 5--Attenuation caused by rain at 15.3 GHz

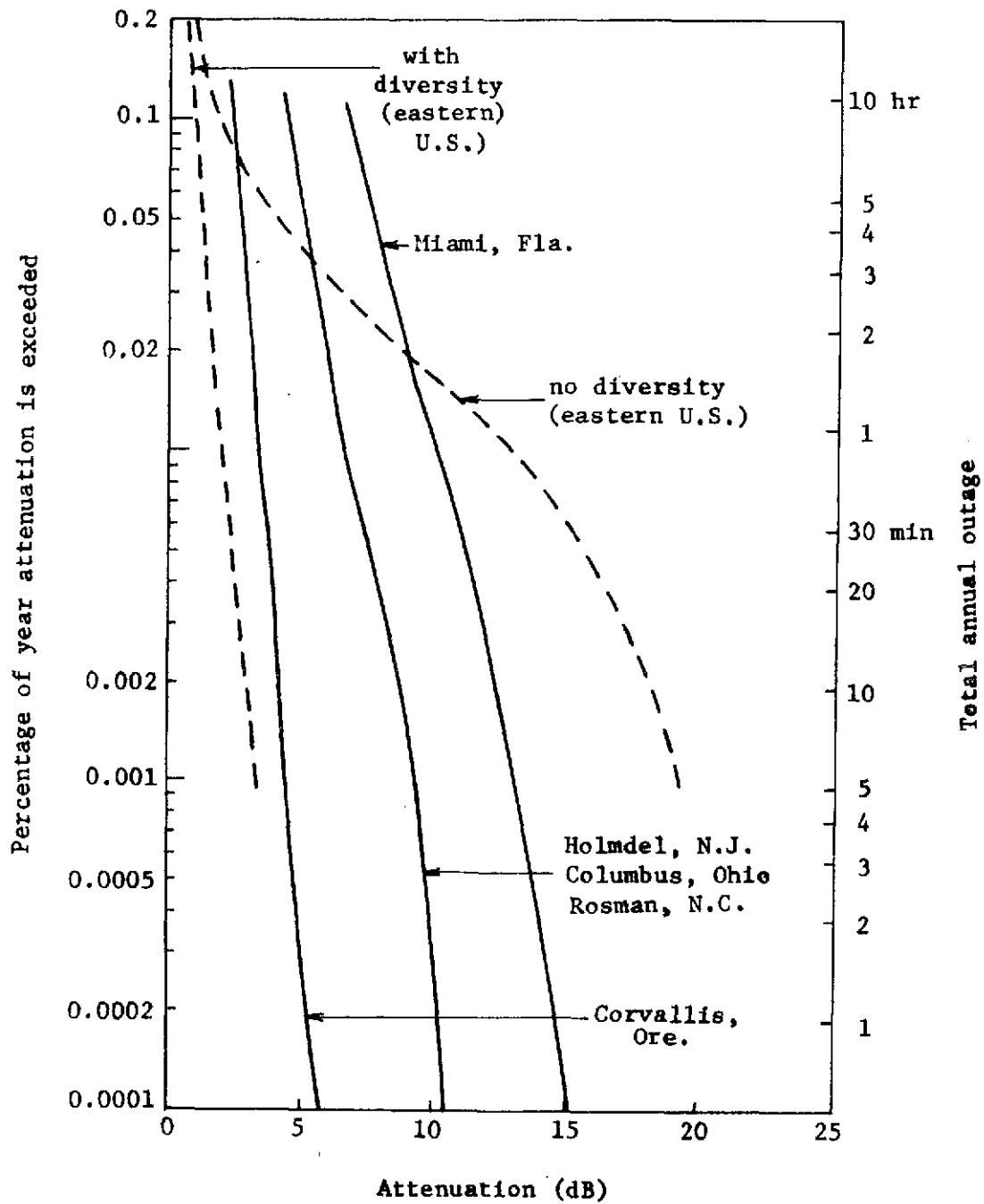


Fig. 6--Attenuation caused by rain extrapolated to 12 GHz

curve shows much less severe fading above the 0.1 percent level and much more severe fading below the 0.01 percent level than the solid curves for any of the locations. A second dashed curve from the same source predicts the net fading statistics for diversity reception at two earth stations separated by about 10 km.

Before any of these data can be compared with the message objectives, account must be taken of the fact that the ordinates in Figs. 5 and 6 are percentages of a year, whereas the message objectives refer to percentages of (the worst) month. The two percentage scales can be reconciled by noting that the fades that occur for very small percentages of the year (less than 0.001 percent or about 5 minutes a year) are probably the result of only a single severe thunderstorm. Hence the monthly percentages associated with these fading levels are simply 12 times the yearly percentage. The fades associated with higher annual percentages (e.g., 0.01 percent of a year or about 1 hour) are due to more commonly occurring storms and it is reasonable to expect that these are distributed among at least 2 or 3 months. In this case, the annual percentage need be multiplied by factors of only 6 or 4 to obtain an estimate of the monthly percentage. Similarly, the fading level for 0.1 percent of the year (about 9 hours total) probably corresponds to no more than 0.2 or 0.3 percent of the worst month.

Applying the foregoing assumptions to the fading data for the worst location (Miami), the curve shown by the solid line in Fig. 7 is obtained. Note that in this figure the ordinate refers to percentages of the worst month. In order to compare the actual fading with that allowed by the message objectives, the dashed curves of Fig. 4 are repeated in Fig. 7 with fading measured relative to the level exceeded 20 percent of the time. It is apparent that, even for Miami, the actual 12 GHz fading is less severe than that permitted by the noise objectives. Thus one can safely design rf links to meet the noise objective for some comparatively high percentage of the time (20 percent, for example) and be confident that, so long as the carrier remains above threshold, the objectives for smaller percentages will be met. It remains only to choose the percentage of time that the link is to remain above threshold.

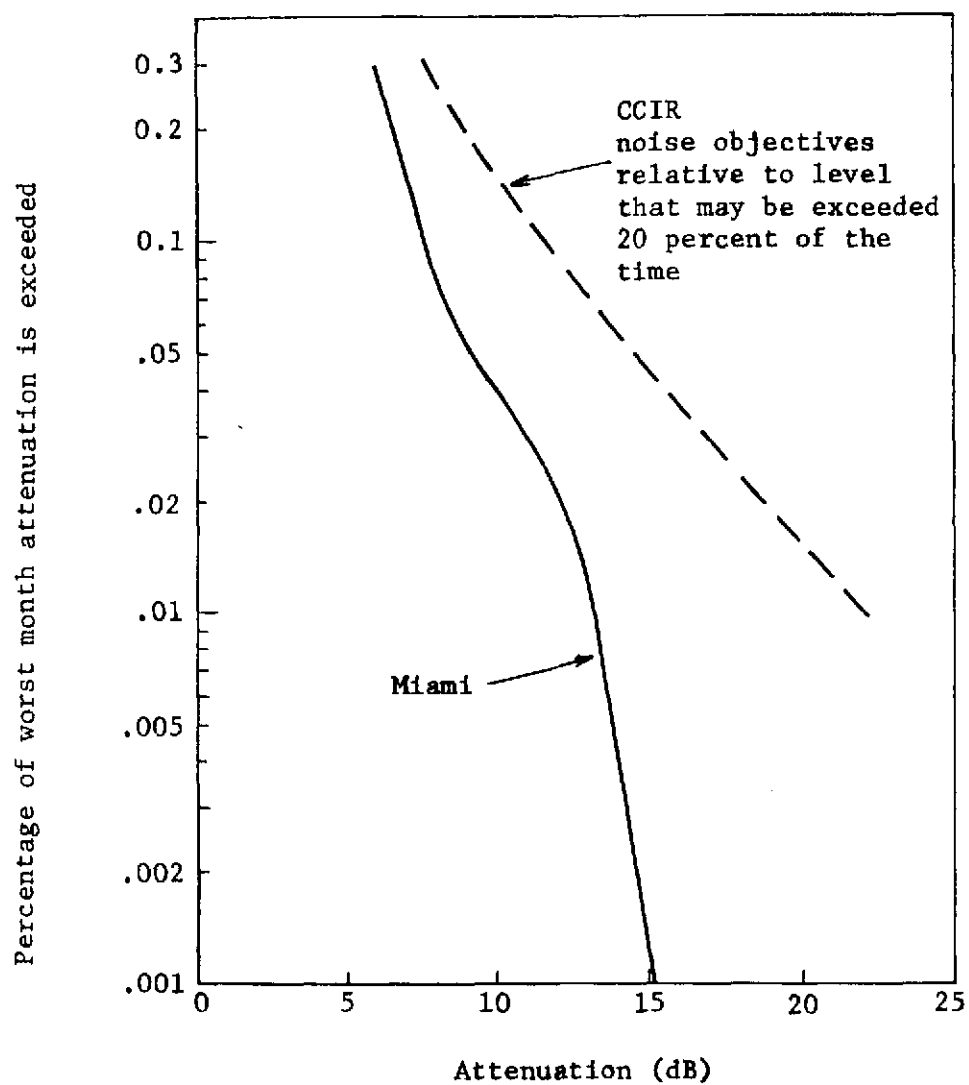


Fig. 7--Comparison of worst monthly fading at 12 GHz with CCIR noise objectives

For the baseline systems, it will be assumed that above-threshold operation is required for at least 99.99 percent of the year in the case of fixed-satellite systems, and 99.9 percent of the year for broadcasting-satellite systems in the domestic regions of heaviest rainfall. Referring to Fig. 6, the corresponding threshold margins for the southeastern part of the United States are 10 and 7 dB, respectively, without diversity reception and 2 and 1 dB with diversity. Links having these nondiversity margins will, of course, provide considerably better service in less-rainy parts of the country. With a 10 dB margin, a fixed-satellite circuit to New Jersey or North Carolina, for example, could expect to remain above threshold for all but a minute or two a year.

BASELINE SYSTEMS

As previously noted, a set of hypothetical reference or baseline line systems is needed for comparative analyses of different strategies for sharing the orbit and spectrum. In order that the results of the strategy comparisons be applicable to future operational systems, the parameters of the baseline systems should not differ greatly from those of systems currently being planned. Examples of a 12 GHz fixed-satellite system proposed by MCI Lockheed in 1971,⁽⁸⁾ and the 12 GHz broadcasting portion of the Communications Technology Satellite (CTS),⁽¹⁸⁾ are shown in Table 4.

At the same time, it is important that the baseline system designs be based on a clearly stated and internally consistent set of performance specifications and a common design approach. The performance specifications adopted for the rf links of the baseband systems were described earlier in this section and are summarized in Table 5 for the four message channels of principal interest: telephone channels in fixed-satellite systems, TV channels in fixed-satellite systems, broadcast TV channels for individual reception, and broadcast TV channels for community reception. Separate carriers will normally be used for each TV channel and its associated audio channel or channels, whereas, with one exception, the carriers used for telephone transmission will usually be modulated by FDM basebands consisting of from 12 to 1800 channels. The exception is single (telephone or data) channel-

Table 4

PARAMETERS OF PROPOSED SYSTEMS

Parameter	Unit	MCIL Fixed Satellite	CTS Broadcasting Satellite
<u>Signal</u>			
Uplink frequency band	GHz	11.7-12.2	
Downlink frequency band	GHz	14.0-14.5	
Channels per transponder	-	600 tel	1 TV
Multiplexing	-	FDM	-
Modulation	-	FM	FM
Transponder bandwidth	MHz	36	108
Signal rf bandwidth	MHz	36	25
Noise objectives		CCIR	CCIR
<u>Uplink Transmitter</u>			
Power to antenna	dBW	30.8	30.0
Antenna diameter	ft	32	16
Beamwidth at 14 GHz	deg	0.14	0.28
On-axis gain	dB	60.5	54.4
On-axis eirp	dBW	91.4	84.4
<u>Uplink Receiver</u>			
Antenna diameters	ft	0.83x1.67	2
Beamwidths at 14 GHz	deg	3.5x7	2.5
Antenna gain	dB	30.5	36.2
System temperature	°K	1200	2315
Figure-of-merit	dB/°K	- 0.7	2.5
<u>Downlink Transmitter</u>			
Net power to antenna	dBW	10.5	20.5
Antenna diameter	ft	2.5	2
Number of beams		2	1
Beamwidths at 14 GHz	deg	2.5 each	2
On-axis gain	dB	{ 30.0 (west) 34.7 (east)	36.3
On-axis eirp	dBW	{ 40.5 (west) 45.2 (east)	58.8
<u>Downlink Receiver</u>			
Antenna diameter	ft	32	16
Beamwidth at 11.7 GHz	deg	0.17	0.34
Antenna gain	dB	59.3	53.1
System temperature	°K	136	1000
Figure-of-merit	dB/°K	38.0	23.1

Table 5

BASELINE PERFORMANCE SPECIFICATIONS

Quantity	Type of Message Channel and System			
	Telephone Fixed Satellite	TV Fixed Satellite	TV Broadcasting Satellite Community Reception	TV Broadcasting Satellite Individual Reception
Overall thermal-noise objective	5000 pWOp	55 dB	49 dB	43 dB
Uplink thermal-noise objective	1000	62	56	50
Downlink thermal-noise objective	4000	56	50	44
Probability of above-threshold operation (% of year)	99.99	99.99	99.9	99.9
Required system margin above threshold for nondiversity operation in southeast U.S. (dB)	10	10	7	7

per-carrier transmission using PCM encoding and PSK modulation as described in detail earlier in this section.

The design approach used to select the parameters of baseline satellites and earth stations capable of supporting rf links which meet the performance specifications of Table 5 consists of four steps. First, the product, EG/T, of satellite eirp-per-carrier and earth-station figure-of-merit required by the downlink noise objectives and the threshold margin is determined for each television and multichannel telephone carrier of interest under conditions of minimum-power or power-limited operation using the EG/T-bandwidth tradeoffs of Fig. 3. These are the minimum values of per-carrier EG/T that must be provided on the corresponding downlinks. They are also "beam edge" requirements, since they apply to all downlinks, and in particular to those where the earth station lies at the edge of the coverage pattern of the satellite antenna. Thus the value of per-carrier EG/T required along the axis of the satellite antenna will be at least 3 dB higher than the values obtained from Fig. 3. The combinations of on-axis power-limited per-carrier EG/T and rf bandwidth are shown in Table 6 for several TV/FM and FDM/FM carriers of interest. Note that if carrier bandwidth is limited to 36 MHz as in the 4 and 6 GHz transponders

Table 6

ON-AXIS, POWER-LIMITED, PER-CARRIER DOWNLINK EG/T AND
RF BANDWIDTH REQUIREMENTS FOR CARRIERS OF VARIOUS SIZES

Type of Message Channel and System	Carrier Size (No. of Channels)	On-Axis per-Carrier EG/T (dBW/°K)	RF Bandwidth (MHz)	Modulation Index (peak)(rms)	
Telephone Fixed Satellite	12	59.5	$W_C = 0.8$	6.94	2.19
	24	62.0	1.4	5.94	1.88
	48	64.3	2.5	5.20	1.64
	96	66.7	4.4	4.46	1.41
	192	69.3	7.8	3.84	1.21
	300	71.1	11.9	3.72	1.18
	600	74.2	23.8	3.73	1.18
	900	75.9	35.7	3.73	1.18
	1200	77.4	47.6	3.72	1.18
	1500	78.2	59.6	3.73	1.18
	1800	78.9	71.5	3.73	1.18
TV Fixed Satellite	1	74.7	$W_C = 27.5$	2.27	-
	1	73.7	$W_D = 21.8$	2.60	-
TV Broadcasting Satellite Community Reception	1	71.1	$W_C = 23.1$	1.74	-
	1	69.8	$W_D = 17.1$	2.04	-
TV Broadcasting Satellite Individual Reception	1	69.8	$W_C = 17.2$	1.05	-
	1	67.8	$W_D = 10.8$	1.29	-

of current Intelsat and domestic satellite systems, operation becomes bandwidth limited for carriers with more than 900 channels.

Having determined per-carrier values of EG/T required on the downlinks, the next step is to decide upon the per-transponder value of EG/T which the baseline combination of satellite transponder and earth station should actually deliver. In specifying this product, the value of E is normally taken as the maximum or saturated eirp of the transponder along the satellite antenna axis. The required value depends on the number and nature of the carriers which the transponder must support.

When the transponder in question is to carry only a single carrier (which usually occupies the entire transponder bandwidth), the full saturated eirp can be used for transmission, and the per-transponder EG/T product can be set equal to the on-axis product required by the carrier. It should be noted in this connection however that it is not necessary to use the minimum or power-limited values of per-carrier EG/Ts tabulated in Table 6. Higher values of EG/T, corresponding to bandwidth-limited operation, may be preferred in the case of heavy trunks. The decision depends on the number of message channels to be carried relative to the transponder bandwidth and on the available transponder eirp. The value of EG/T required for any specific combination of rf bandwidth and number of telephone channels may be read from Fig. 3.

In fixed-satellite systems, a single satellite transponder is often used to relay two or more carriers, and the maximum power of the transponder cannot be used. Instead, the output power of its high-power amplifier (HPA) must be "backed off" about 6 dB from the maximum single carrier value so that intermodulation noise in the message channels will remain within specified limits. For the same reason, "guard bands" are normally allowed between the carriers with the result that the total rf bandwidth occupied by the carriers is from 10 to 20 percent less than the nominal rf bandwidth of the transponder.

To take this factor into account, and to ensure reasonably effective use of the spectrum by transponders carrying multiple carriers, the baseline systems will be designed on the principle that the transponder must be powerful enough to support multiple FDM/FM carriers occupying a total of about 85 percent of its effective bandwidth when using the largest earth stations in the system. In applying this principle, the power-limited per-carrier EG/T requirements of Table 6 will be used.

An example featuring 9 carriers, carrying from 24 to 192 simplex (one-way) telephone channels and occupying about 31 MHz of the assumed 36 MHz transponder bandwidth, is given in Table 7a. It suggests that

Table 7

EXAMPLES OF EG/T REQUIREMENT FOR MULTICARRIER OPERATION
OF 36 MHz FIXED-SATELLITE SYSTEM TRANSPONDERS

Number of Carriers	Carrier Size	Total Channels	Bandwidth per Carrier ^a (MHz)	Total Bandwidth (MHz)	EG/T per Carrier ^a (dBW/°K)	Total EG/T (dBW/°K)
a. Nine FDM/FM Carriers						
4	24	96	1.4	5.6	62.0	68.0
2	48	96	2.5	5.0	64.3	67.3
1	96	96	4.4	4.4	66.7	66.7
2	192	384	7.8	15.6	69.3	72.3
Totals	9	672		30.6		75.2
(On-axis saturated EG/T of transponder = $75.2 + 6 = 81.2$ dBW/°K)						
b. Three FDM/FM Carriers						
1	192	192	7.8	7.8	69.3	69.3
2	300	600	11.9	23.8	71.1	74.1
Totals	3	792		31.6		75.3
(On-axis saturated EG/T of transponder = $75.3 + 6 = 81.3$ dBW/°K)						

^aFrom Table 6.

the product of the saturated on-axis eirp of the satellite transponder and the figure-of-merit of the earth station should be not less than about 81 dBW/°K. The combined capacity of the 9 carriers is 672 telephone channels. Another example featuring 3 carriers is shown in Table 7b and leads to a similar result of 81.3 dBW/°K for a combined capacity of 792 channels occupying 31.6 MHz of transponder bandwidth. It is concluded that a 12 GHz transponder with a 36 MHz rf bandwidth should be paired with an earth station such that the nominal saturated on-axis per-transponder EG/T product is 81 dBW/°K. If transponders of greater bandwidth are used, the EG/T product should be increased accordingly if the same fraction of the bandwidth is to be used for multiple carriers having the prescribed noise objectives. For example, a 108 MHz transponder would require an EG/T of 86 dBW/°K.

If all of the transponders on a fixed-satellite are identical, those used for only a single carrier will have a capacity greater than those used for several smaller carriers because of the power backoff

required by multicarrier operation. For the transponder-earth-station combination with an EG/T product of 81 dBW/°K derived in Table 7, Fig. 3 shows that a capacity of about 1500 telephone channels could be supported with a worst-channel noise of 4000 pWOp. Operating into earth stations with a given figure-of-merit, the single-carrier capacity is thus about double that for multiple-carrier operation. The system margin above threshold (but not above the noise objective) is also higher by about 8 dB.

The third step in the baseline system design approach is to decide how to split the on-axis, saturated, downlink, per-transponder EG/T product between satellite eirp and earth-station figure-of-merit. Logically, this decision should be one which, within certain operational constraints on earth-station antenna size, minimizes total system cost. Using the discussion of Sec. II and the examples of Table 4 as guides to this division, the three satellites and four ground receiving stations described in Table 8 appear to be reasonable representatives for use in baseline systems supporting the two types of broadcasting-satellite reception and in fixed-satellite systems capable of providing downlinks of various capacities.

The indicated division of satellite eirp between transponder output power and satellite antenna gain is based on the use of single-feed circular or elliptical parabolic antennas having the indicated beamwidths. In the fixed-satellite service the beamwidths for both uplinks and downlinks are based on the condition that the antenna footprint covers the contiguous 48 states. The satellite antenna beamwidths for the uplinks to broadcasting satellites are based on the same condition, so that programming may be transmitted to such satellites from any location in the country. In the case of broadcasting downlinks, a 2.3 deg circular beam is assumed for community reception within a multistate region, and a 1.7 deg x 3.3 deg elliptical beam for individual reception within a time zone.

The output power indicated for the baseline fixed-satellite transponder is about 6 dB higher than that shown for the proposed MCI Lockheed system in Table 4. However, the baseline transponder power could be reduced several dB without compromising message noise objectives by following the proposal of the MCI Lockheed Satellite Corporation and

Table 8
BASELINE SYSTEM PARAMETERS

Parameter	Unit	Fixed-Satellite		Broadcasting-Satellite	
		Terminal		Community Reception	Individual Reception
		Large	Small		
a. Downlink					
Satellite Transponder					
End-of-life net power to antenna	dBW	16		16	22
Antenna diameter	ft	0.86x1.72		2.33	1.65x3.3
Antenna beamwidth	deg	3.5x7		2.3	1.7x3.3
Antenna gain	dB	30		36	36
On-axis saturated eirp	dBW	46		52	58
Rf bandwidth	MHz	36		25	18
Earth-Station Receiver					
Antenna diameter	ft	32	16	12	3
Antenna beamwidth	deg	0.17	0.34	0.45	1.8
Antenna gain	dB	59	53	51	39
System temperature	°K	250	250	500	500
On-axis figure-of-merit	dBW/°K	35	29	24	12
Downlink per transponder EG/T	dBW/°K	81	75	76	70
b. Uplink					
Earth-Station Transmitter					
Net power to antenna	dBW	30 ^a	30 ^a	30 ^a	
Antenna diameter	ft	32	16	16	
Antenna beamwidth	deg	0.16	0.32	0.32	
Antenna gain	dB	60.5	54.5	54.5	
On-axis eirp	dBW	90.5 ^a	84.5 ^a	84.5	
Satellite Transponder					
Antenna diameter	ft	1.44x0.72		1.44x0.72	
Antenna beamwidth	deg	3.5x7		3.5x7	
Antenna gain	dB	30		30	
System temperature	°K	1200		1200	
On-axis figure-of-merit	dBW/°K	-1		-1	
Maximum uplink EG/T	dBW/°K	89.5 ^a	83.5 ^a	83.5	

^aExample only. In practice, earth-station power output and eirp are adjusted to match size of carrier.

using a dual-feed satellite antenna that directs higher gain towards the eastern and southeastern part of the country where the required system margins are higher.⁽⁸⁾

The output power indicated for the broadcasting-satellite transponder also depends in a similar way on the nature of the satellite antenna pattern and on the system margin required in the service area of the satellite. If the service area is smaller than a time zone, or has less rainfall than the southeastern United States, correspondingly lower powered transponders may be used.

Comparing the per-transponder EG/T and bandwidth requirements from Tables 6 and 7 with the baseline equipment parameters shown in Table 9, it is concluded that the nominal maximum capacities of the baseline fixed-satellite transponder for single carrier and multi-carrier operation with the large (32 ft) baseline earth station are 1500 and 700 telephone channels, respectively. The corresponding capacities with the smaller (16 ft) earth station are 600 and about 200 channels, respectively. The bandwidths of the broadcasting-satellite transponder were chosen to permit minimum-power transmission of one television channel in its Carson's-rule bandwidth and also to bear a simple relationship to the fixed-satellite transponder bandwidth to facilitate interservice frequency planning.

The last step in defining the equipment parameters of the baseline systems is to choose the earth-station and satellite parameters for the uplinks. Since the carrier bandwidths are the same as on the downlinks, it is only necessary to ensure that the uplinks can provide the required values of per-carrier EG/T. For any given carrier, the on-axis uplink EG/T requirement will be about 7.5 dB higher than the corresponding downlink value shown in Table 6 to allow for the 6 dB lower noise objective and 1.5 dB higher path loss. The uplink parameters shown in Table 8b are appropriate to the maximum single-carrier capacity of the associated transponder. Earth stations transmitting smaller carriers would use proportionally lower eirps.

It will be noted that the uplinks for both types of satellite-broadcasting reception are identical to those for the 16 ft fixed-satellite uplink. Although this represents overdesign for the individual reception systems, it enhances the homogeneity of the uplinks

(which, in any case, are all in the fixed-satellite service) and, as will be seen, reduces intersystem interference.

To complete the description of the baseline systems, it is necessary to indicate the deployment of satellites and earth stations. The determination of preferred satellite deployments is of course the key problem in the analysis of sharing tactics and strategies and will be addressed at length in Secs. V and VI. The locations assumed for the earth stations to be served by fixed-satellite systems and the service areas to be covered by the baseline broadcasting-satellite systems are shown in Tables 9 and 10, respectively. Uplink transmitter locations and the points on the ground at which the satellite transmitting antennas are aimed are also indicated in these tables. It will be noted that the broadcasting-receiver sites in Table 10 lie on the service area boundaries, since both noise and interference levels will be highest here.

Table 9

FIXED-SATELLITE AIM POINT AND EARTH-STATION LOCATIONS

Station	Code	North Latitude (deg)	West Longitude (deg)
Satellite aim point	AF	39	98
Atlanta, Ga.	ATL	33.7	84.4
Boston, Mass.	BOS	42.3	71.1
Chicago, Ill.	CHI	41.9	87.6
Cincinnati, Ohio	CIN	39.1	84.5
Dallas, Texas.	DAL	32.8	96.8
Denver, Colo.	DEN	39.8	105.0
Detroit, Mich.	DET	42.3	83.1
Washington, D.C.	DC	38.9	77.0
Kansas City, Mo.	KC	39.0	94.7
Los Angeles, Calif.	LA	34.1	118.3
Miami, Fla.	MIA	25.8	80.2
New Orleans, La.	NO	29.9	90.1
New York, N.Y.	NY	40.8	73.9
San Francisco, Calif.	SF	37.8	122.4
Seattle, Wash.	SEA	47.6	122.3

Table 10

BROADCASTING-SATELLITE AIM POINTS AND RECEIVING SITES

Station	Code	North Latitude (deg)	West Longitude (deg)
1. Eastern Time Zone			
Uplink transmitter	NY	40.8	73.9
Satellite aim point	ABI	37	79
Northeast corner	INE	47	68
South central	IS	25.8	80.2
Northwest corner	INW	47.5	86.5
West central	IW	37	86.5
Southwest corner	ISW	31	86.5
2. Central Time Zone			
Uplink transmitter	CHI	41.9	87.6
Satellite aim point	AB2	37	94
Northeast corner	2NE	47.5	86.5
East central	2E	37	86.5
Southeast corner	2SE	31	86.5
Northwest corner	2NW	49	101
West central	2W	38	101
Southwest corner	2SW	30	101
3. Mountain Time Zone			
Uplink transmitter	DEN	39.8	105
Satellite aim point	AB3	39	108
Northeast corner	3NE	49	101
East central	3E	38	101
Southeast corner	3SE	30	101
Northwest corner	3NW	49	113.5
West central	3W	39	113.5
Southwest corner	3SW	32	113.5
4. Pacific Time Zone			
Uplink transmitter	LA	34.1	118.3
Satellite aim point	AB4	39	119
Northeast corner	4NE	49	113.5
East central	4E	39	113.5
Southeast corner	4SE	32	113.5
Northwest corner	4NW	47.5	122.3

Finally, a reference set of fixed-satellite links between pairs of the earth stations shown in Table 9 is listed in Table 11. These are the links that will be used routinely in computer simulation of sharing strategies to determine interference levels at the outputs of the fixed-satellite circuits.

Table 11
BASELINE FIXED-SATELLITE LINKS^a

Link	From	To	Link	From	To	Link	From	To
1	NY	LA	26	LA	DEN	51	SF	CHI
2	NY	CHI	27	LA	SEA	52	KC	NY
3	NY	ATL	28	LA	MIA	53	KC	LA
4	NY	DEL	29	LA	SF	54	KC	CHI
5	LA	NY	30	LA	KC	55	NO	NY
6	LA	CHI	31	LA	NO	56	NO	LA
7	LA	ATL	32	LA	DC	57	NO	CHI
8	LA	DAL	33	CHI	DEN	58	DC	NY
9	CHI	NY	34	CHI	SEA	59	DC	LA
10	CHI	ATL	35	CHI	MIA	60	DC	CHI
11	CHI	DAL	36	CHI	SF	61	NY	BOS
12	CHI	LA	37	CHI	KC	62	NY	CIN
13	DAL	NY	38	CHI	NO	63	NY	DET
14	DAL	CHI	39	CHI	DC	64	LA	BOS
15	DAL	LA	40	DEN	NY	65	LA	CIN
16	ATL	NY	41	DEN	LA	66	LA	DET
17	ATL	CHI	42	DEN	CHI	67	CHI	BOS
18	ATL	LA	43	SEA	NY	68	CHI	CIN
19	NY	DEN	44	SEA	LA	69	CHI	DET
20	NY	SEA	45	SEA	CHI	70	BOS	NY
21	NY	MIA	46	MIA	NY	71	BOS	LA
22	NY	SF	47	MIA	LA	72	BOS	CHI
23	NY	KC	48	MIA	CHI	73	CIN	NY
24	NY	NO	49	SF	NY	74	CIN	LA
25	NY	DC	50	SF	LA	75	CIN	CHI

^aFor city code, see Table 9

IV. INTERFERENCE PERFORMANCE

When two or more radio communication systems share a band of frequencies, the quality of service they provide is determined not only by the levels of thermal noise and intermodulation as discussed in the preceding section, but also by the amount of intra- and intersystem interference. The key problem in devising satisfactory strategies for sharing the orbit-spectrum resource is to find system deployments that keep such interference to acceptably low levels. In this section, the general equations and antenna pattern models needed to compute interference levels for specified configurations of fixed- and broadcasting-satellite systems are given. The treatment is rather detailed because it is intended to serve as the basis for a comprehensive computer program for interference prediction.

DEPENDENCE OF OUTPUT MESSAGE QUALITY ON RF INTERFERENCE

The ultimate effect of the interfering or unwanted rf signals that enter a link at the inputs to the satellite transponder and the earth-station receiver is to degrade the quality of the messages carried by the link. Just as when the unwanted signal is thermal noise, the method of specifying this impairment of quality depends on the nature of the messages, but in all cases, the measure of message quality can be related to the ratios of wanted-to-unwanted signal power measured at the uplink and downlink receiver inputs.

Telephone Channels

For a telephone channel, the effect of rf interference on message quality may be specified in terms of the signal-to-interference ratio S/I at the channel output. In this ratio, S is the power of a signal representing a speaker and I is the interference noise power, after psophometric weighting to account for the frequency response of the human ear.

When analog methods of multiplexing and modulation such as FDM/FM are used, and there is only a single interfering signal, the relation between S/I and C/X is a simple proportionality

$$S/I = RC/X$$

providing that C/X is greater than the modulation threshold. As in the case of thermal noise, the proportionality constant R is called the receiver transfer characteristic (RTC). Its numerical value depends on the position of the telephone channel in the wanted signal baseband, the spectral characteristics of the wanted and unwanted signals as determined by the number of channels carried by each and the modulation index or rf bandwidth used, and on the frequency separation or offset between the wanted and unwanted carriers. The value of the RTC also depends on the type of reference signal used to represent speech power in the telephone channel--e.g., a sinusoidal test tone, or the amount of noise that appears in the channel when the FDM baseband is represented by white noise.

Values of RTC have been calculated or measured only for cases of a single unwanted signal. However, when there are many small unwanted signals, each may be treated independently using the value of R appropriate to that signal, and the resultant interference-to-signal ratio at the output of a selected telephone channel obtained by summing the interference-to-signal ratios that would be produced by each unwanted signal acting alone.⁽²⁷⁾ Thus, the interference-to-signal ratio for a telephone channel carried by the i th link is given by

$$\left(\frac{I}{S}\right)_i = \sum_{j=1}^N \frac{1}{R_{ij}} \left(\frac{X_{ij}}{C_i}\right)_{up} + \sum_{j=1}^N \frac{1}{R_{ij}} \left(\frac{X_{ij}}{C_i}\right)_{down} \quad (21)$$

where N is the total number of interfering links and the primes on the summations indicate that the term for $j = i$ is omitted.

In this expression, the first summation accounts for interference entering at the input to the uplink (satellite) receiver and the second for interference entering the downlink (earth station) receiver, Where double subscripts are used, the first identifies the wanted link and the second the unwanted link. Thus $(X_{ij}/C_i)_{up}$ is the reciprocal wanted-to-unwanted signal ratio at the input to the uplink receiver

on link i resulting from interference from the uplink transmitter on link j , and R_{ij} is the corresponding RTC for the telephone channel in question. The same value of R_{ij} is shown for the uplink and downlink because it is assumed that no signal processing takes place in the satellites. As a practical matter, R_{ij} will be sensibly infinite, and the corresponding interference term negligible, when the spectra of the wanted and unwanted signals do not overlap.

An alternative, and more commonly used, measure of the effect of radio-frequency interference at the output of a telephone channel is the interference noise power I in pWOp. At such a point the signal power of a sinusoidal test tone is, by definition, $1\text{mW} = 10^9 \text{ pW}$, so it follows from Eq. (21) that

$$I_i = \sum_{j=1}^N (I_{ij})_{\text{up}} + \sum_{j=1}^N (I_{ij})_{\text{down}} \quad (22)$$

where

$$(I_{ij})_{\text{up}} = \frac{10^9}{R_{ij}} \left(\frac{X_{ij}}{C_i} \right)_{\text{up}}$$

and

$$(I_{ij})_{\text{down}} = \frac{10^9}{R_{ij}} \left(\frac{X_{ij}}{C_i} \right)_{\text{down}}$$

are, respectively, the uplink and downlink interference contributions from link j into link i .

Thus, for a link carrying an FDM/FM signal, the problem of interference prediction reduces to the computation of the receiver transfer characteristic and the unwanted-to-wanted signal ratio for each interfering uplink and each interfering downlink. The former shows the

dependence of output interference on the parameters of the wanted and unwanted signals, the latter the dependence on equipment and propagation parameters. The equations needed for these computations will be given in following subsections.

Television Channels

When the link carries a television channel, the effect of rf interference on the quality of the television picture is not easily described in terms of a signal-to-interference ratio at the channel output unless the interference can be represented as gaussian noise. Even in the case of noise-like interference, the correspondence between the output signal-to-interference ratio and subjective evaluations of picture quality must be established by experimental measurements with groups of television viewers. Indeed, it is common practice to express the results of such measurements by relating grades of picture quality^(37,38) (for example, excellent, good, fair, poor) directly to the wanted-to-unwanted signal ratio C/X at the receiver input. In particular, the value of C/X corresponding to a specified picture grade and a specific kind of unwanted signal is called the interference protection ratio, or simply protection ratio, for that picture quality and type of interference.

For a link carrying a television channel, it is thus sufficient to calculate the effective wanted-to-unwanted signal ratio at the input to the downlink receiver and to compare it with the protection ratio data to infer the resultant picture quality on the link. As in the case of the RTC, however, numerical values of protection ratio are available only for cases of a single unwanted signal. When there are several unwanted signals, it is necessary to take into account the fact that they are likely to differ in the amount of picture degradation they cause, not only because of differences in signal strength but also because of intrinsic differences in their ability to affect the wanted signal, as reflected by the protection ratio measurements. Therefore, the effective unwanted-to-wanted signal ratio for the television channel carried by the i th link will be written

$$\left(\frac{X}{C}\right)_i = \sum_{j=1}^N \frac{1}{Q_{ij}} \left(\frac{X_{ij}}{C_i}\right)_{\text{up}} + \sum_{j=1}^N \frac{1}{Q_{ij}} \left(\frac{X_{ij}}{C_i}\right)_{\text{down}} \quad (23)$$

where the notation conventions are the same as in Eq. (21), and Q_{ij} is an interference sensitivity factor that indicates the interfering effect of the j th interfering signal relative to that of a reference interference signal identical to the wanted signal on link i .

Adopting the protection ratio for barely perceptible interference as a measure of interference sensitivity, Q_{ij} will be taken as the ratio of the protection ratio for the wanted signal against interference from a reference interfering signal to that for interference from the actual unwanted signal.

With the aid of Eq. (23) the problem of interference prediction for a link carrying a television signal reduces to the computation of the sensitivity factor and the unwanted-to-wanted signal ratio for each interfering uplink and each interfering downlink. The necessary data will be given in the balance of this section.

RECEIVER TRANSFER CHARACTERISTICS, PROTECTION RATIOS, AND SENSITIVITY FACTORS

As explained in connection with Eqs. (21) and (23), the effect on message quality of all the unwanted rf signals to which the uplink and downlink receivers on a satellite link are exposed can be calculated as the sum of the effects of each signal acting individually. Each individual effect in turn is just the product of the relative strength of the unwanted signal, and its relative potential for interfering with the wanted signal. The former factor is given by the reciprocal carrier-to-interference ratio X_{ij}/C_i and the latter factor by the reciprocal of either the receiver transfer characteristic R_{ij} (for telephone channels), or the sensitivity factor Q_{ij} (for television channels).

In this subsection, equations for R_{ij} will first be given for interference to an FDM/FM from either another FDM/FM signal or from a television FM signal (TV/FM). Then, empirical equations for Q_{ij}

will be given for interference to a TV/FM signal from either another TV/FM signal or from an FDM/FM signal.

Receiver Transfer Characteristics for Interference to an FDM/FM Signal

When the signal on the wanted (ith) link is frequency modulated by a number of telephone channels in frequency division multiplex, and the unwanted (jth) signal is another FDM/FM signal, the RTC is dependent principally on the modulation indices and the carrier frequency separation of the two signals. In particular, if the modulation on both signals is wideband (rms modulation index greater than unity), the carrier components will be negligibly small, the power spectra will have a gaussian shape, and it can be shown theoretically^(22,39) that the RTC for the highest frequency telephone channel in the FDM baseband is given by

$$R_{ij} = R_{FF}(m_i, m_j, f_d) = \frac{\sqrt{8\pi} m_i^2 m_j w_n w_p f(n_i)}{\exp[-(1+v)^2/(2m^2)] + \exp[-(1-v)^2/(2m^2)]} \quad (24)$$

where

$$f(n_i) = \frac{f_{mk}}{bg^2(n_i)} = \begin{cases} 1.71n_i^{0.6}, & 12 \leq n_i < 240 \\ 42.8, & n_i \geq 240 \end{cases} \quad (25)$$

$$m_k = [W_k / (2f_{mk}) - 1] / \sqrt{\Lambda_k} \quad (26)$$

= rms modulation index on link k (k = i, j)

Λ_k = baseband peak-to-average power ratio on link k

W_k = Carson's-rule bandwidth of signal on link k

$f_{mk} = 0.0042 n_k$

= maximum baseband frequency on link k (MHz)

n_k = number of telephone channels carried by link k

$$m = [m_i^2 + (f_{mj}m_j/f_{mi})^2]^{1/2} \quad (27)$$

= composite rms modulation index

$v = f_d/f_{mi}$ = normalized carrier frequency offset

$f_d = f_j - f_i$ carrier frequency offset

and the quantities W_n , W_p , $g(n)$, and b were defined in connection with Eq. (4) of Sec. III. For identical ($n_j = n_i$, $m_j = m_i$), co-channel ($f_d = 0$) signals, a good approximation to Eq. (24) is ⁽³⁹⁾

$$R_{ij} = (1 + 9.5 m_i^3) W_n f(n_i) \quad (28)$$

In these equations, the expression for m_k is an approximation based on Carson's rule for rf bandwidth, and the expression for f_{mk} is also an approximation, since the ratio f_{mk}/n_k actually varies somewhat with n_k . As in Sec. II, the value of the peak-to-average power ratio A_k will be set equal to 10.

Values of the receiver transfer characteristic R_{FF} based on an approximation ⁽²³⁾ equivalent to Eq. (24) when m_i and m_j are greater than unity, but also valid for smaller values of modulation index, are plotted in Fig. 8 as a function of carrier offset for various values of the composite modulation index defined in Eq. (27).

When the unwanted signal is TV/FM, the available theoretical predictions ⁽⁴⁰⁾ shown in Fig. 9 suggest that the dependence of the RTC on the modulation index of the unwanted signal is not strong except for small f_d . Indeed, unless the curves for TVA and TVB in Fig. 9b (based on Fig. 4-11 of Ref. 40) are incorrectly labeled, it would appear that, for co-channel operation ($f_d = 0$), the relative interference effectiveness of TVA and TVB reverses as the rms modulation index of the wanted FDM/FM signal is decreased from 1 to 0.5.

In any case, if the differences in RTC near $f_d = 0$ are ignored by taking an average of the curves for TVA and TVB, the RTC can be represented by an expression ⁽²²⁾ having the same form as Eq. (24).

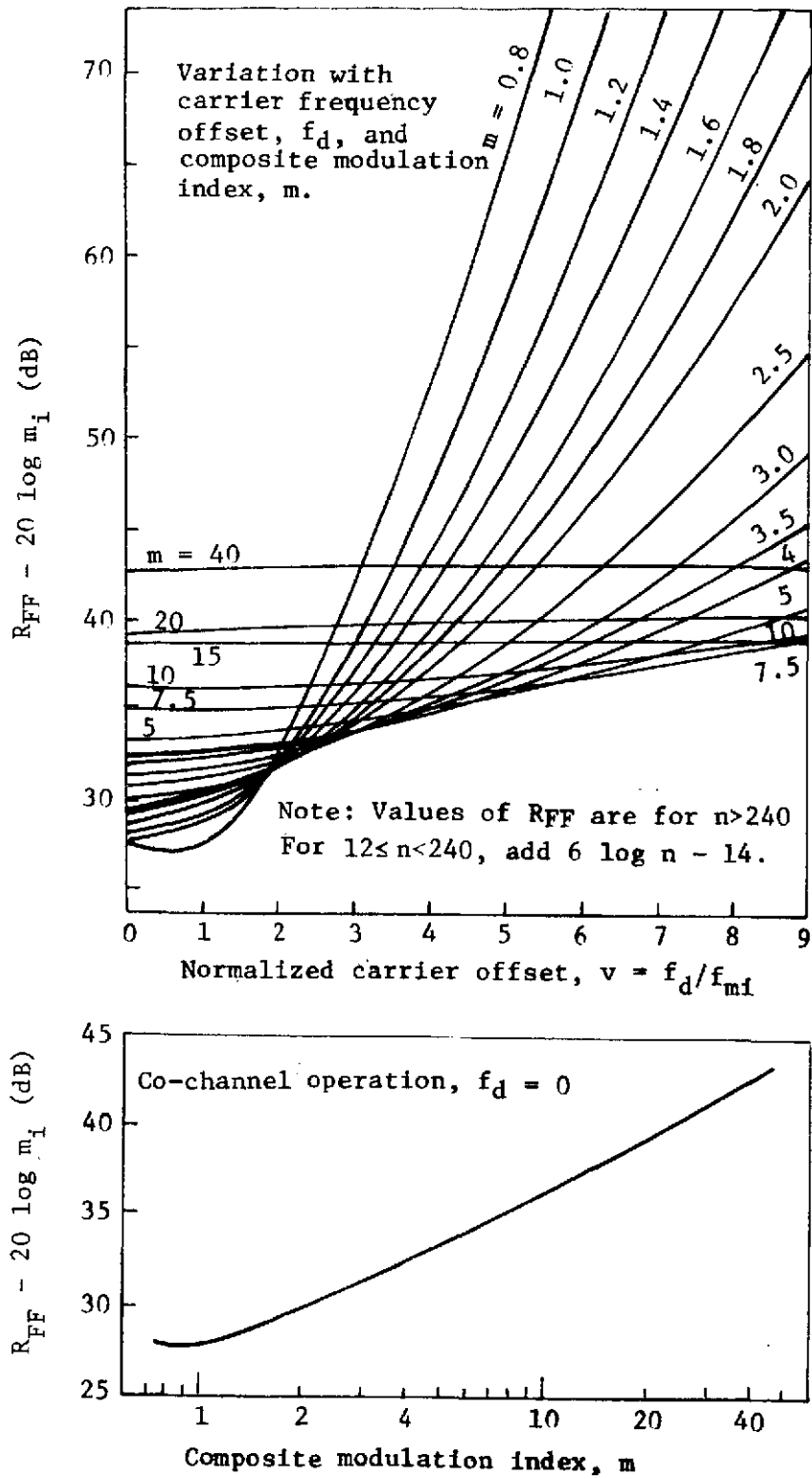
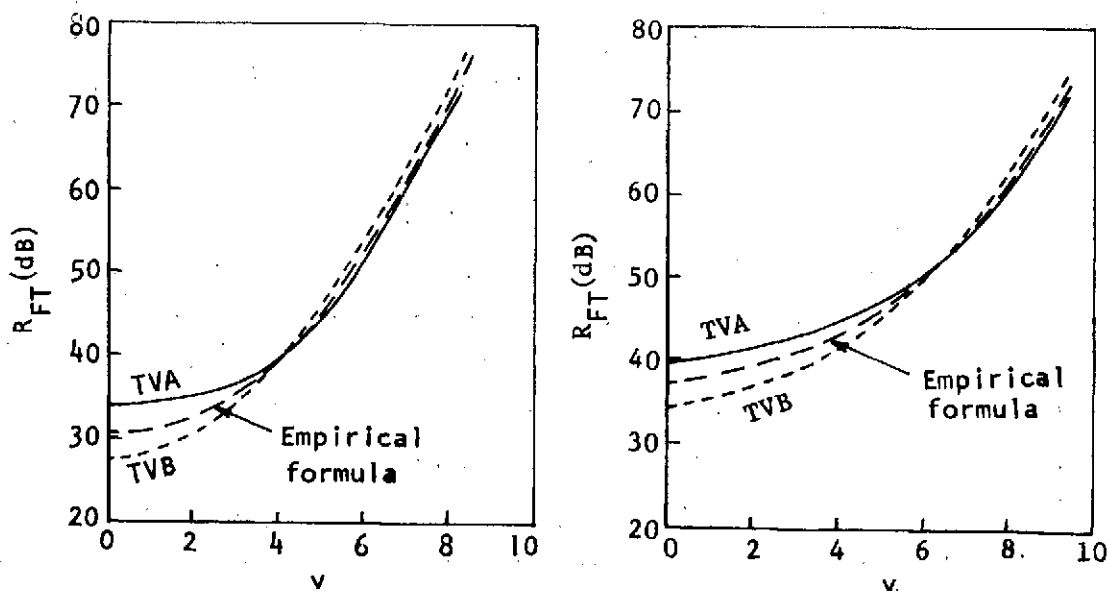
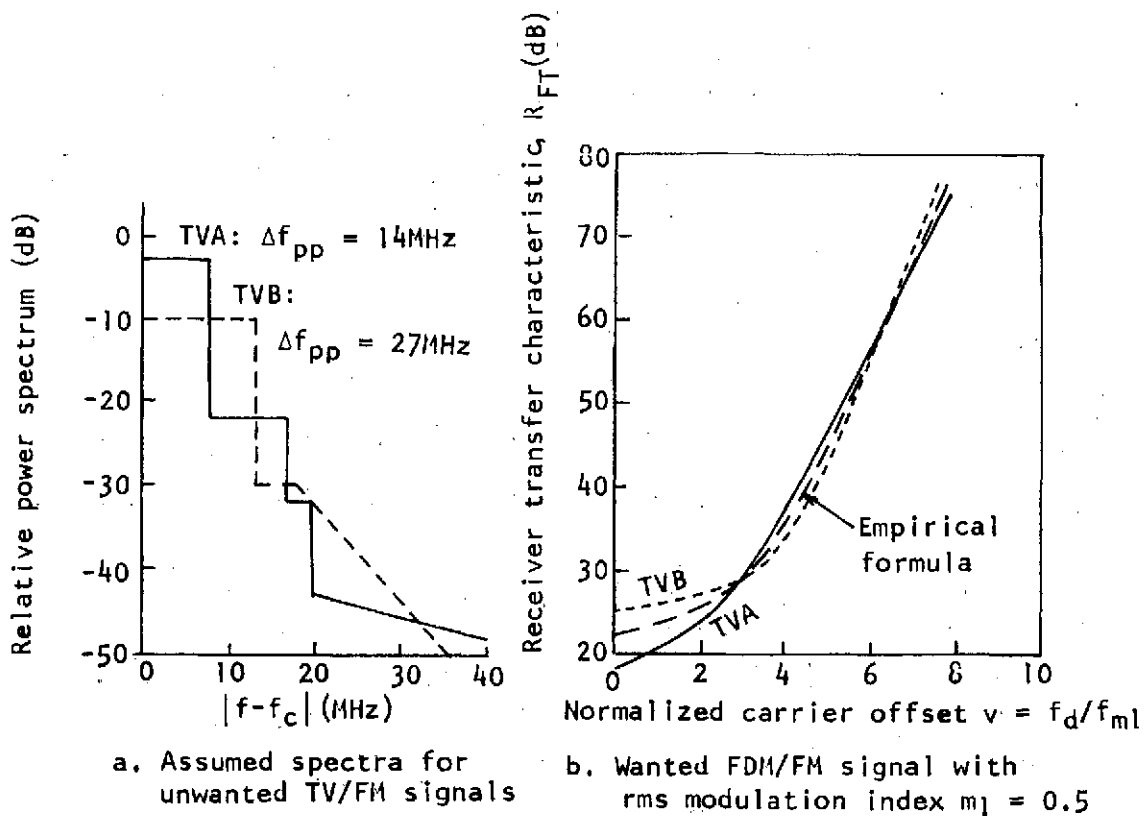


Fig. 8--Receiver transfer characteristic for interference between two preemphasized FDM/FM signals



Note: Values of R_{FT} are for $n \geq 240$. For $12 \leq n < 240$, add $6 \log n - 14$.

Fig. 9--Receiver transfer characteristic for interference to a preemphasized FDM/FM signal from a TV/FM signal

$$R_{ij} = R_{FT}(m_i, f_d) = \frac{(0.2 + 8 m_i^3) w_n w_p f(n_i)}{\exp[-(1+v)^2/h(m_i)] + \exp[-(1-v)^2/h(m_i)]} \quad (29)$$

where

$$h(m_i) = 1.7(1.85 + m_i^2) \quad (30)$$

and all of the other symbols have the same meanings as before. This empirical formula for R_{FT} is plotted as a dashed line in Fig. 9.

Protection Ratios and Interference Sensitivity Factors for Interference to TV/FM Signals

The interference sensitivity factor Q_{ij} was defined as the ratio of the protection ratio for the wanted signal against interference from an identical reference signal to its protection ratio against interference from the actual unwanted signal. Thus, if the unwanted signal is another TV/FM signal

$$Q_{ij} = Q_{TT}(M_i, M_j, f_d) \equiv \frac{\rho_{TT}(M_i, M_i, 0)}{\rho_{TT}(M_i, M_j, f_d)} \quad (31)$$

where $\rho_{TT}(M_i, M_j, f_d)$ is the protection ratio for barely perceptible interference to a TV/FM signal with peak modulation index M_i and carrier frequency f_i from a TV/FM signal with peak modulation index M_j and carrier frequency $f_j = f_i + f_d$.

Before presenting an equation for the dependence of ρ_{TT} on M_i , M_j , and f_d , it may be useful to comment on the general state of knowledge concerning protection ratios for TV/FM signals. Unfortunately, no satisfactory theoretical predictions are available, and the published experimental data are far from being complete and unambiguous. There are several reasons for this. To begin with, the rating scales used to define picture quality in the various experiments differ both in the number of levels (5, 6, or 7) and in the description of the

levels (some are defined in terms of the perceptibility of interference, others in terms of the annoyance it causes, and still others as a conditional mixture of perceptibility and annoyance). In addition, the value of protection ratio obtained from subjective tests is quite sensitive, not only to the modulation parameters of the unwanted, and especially the wanted, signals and to the difference, or offset, in their carrier frequencies, but also to the nature of the picture (still, moving, amount of detail) on each signal. Here again there is little agreement among the available measurements.

Yet another source of confusion in interpreting protection-ratio data arises from the use of different criteria for assessing interference effects in the presence of significant thermal noise. Most of the published measurements give the protection ratio corresponding to "barely perceptible" interference in the presence of an amount of thermal noise specified by giving the ratio of picture (or luminance) signal amplitude-to-weighted rms noise at the receiver output. In effect, the viewer is shown a picture degraded by noise only and then asked to determine for the picture grade associated with that noise level, the level of interference corresponding to the threshold of bare perceptibility. The resultant values of protection ratio are roughly proportional to the picture signal-to-noise ratio because of the tendency of noise to "mask" the effects of interference. That is, the lower the signal-to-noise ratio, the higher the barely perceptible level of interference, and hence the lower the protection ratio.

With a number of qualifications, the CCIR has published⁽⁴¹⁾ an empirical formula which reflects the dependence of protection ratio, measured for zero carrier offset, in the manner just described on the output picture signal-to-noise ratio S_p/N_w of the wanted television signal

$$10 \log \rho_{TT} = \begin{cases} PC - [49 - 10 \log (S_p/N_w)], & 10 \log (S_p/N_w) < 49 \text{ dB} \\ PC, & 10 \log (S_p/N_w) \geq 49 \text{ dB} \end{cases} \quad (32)$$

The quantity PC was called the "protection constant," although it is clear from Eq. (32) that it is simply the protection ratio for output signal-to-noise ratios exceeding 49 dB. The numerical value of the protection constant depends on the peak-to-peak deviations, Δf_{ppi} and Δf_{ppj} , of the wanted and unwanted signals. This dependence, derived in an unspecified manner at the 1971 Special Joint Meeting of CCIR study groups (SJM) from data on both 525-line and 625-line systems is shown in the following table:

Δf_{ppi} (MHz)	Δf_{ppj} (MHz)	PC (dB)
8	8	36
	≥ 15	34
16	≤ 10	28
	16	30
	≥ 20	28
24	≤ 18	25
	24	27

The other criterion used in protection-ratio measurements asks the viewer to grade the overall quality of a picture that has been degraded by a specified combination of both noise and interference. The protection ratios determined for a given picture grade by this criterion tend to be inversely proportional to signal-to-noise ratio, since it is the combined noise and interference rather than a predominant amount of noise that determines the picture grade to which the protection ratio corresponds.

Recent measurements with 525-line TV/FM systems using this criterion for protection-ratio measurement⁽⁴²⁾ suggest values of protection constant for $\Delta f_{ppi} = \Delta f_{ppj} = 18$ MHz, that are at least 15 dB lower than those implied by the SJM table. Part of this difference can be

explained by the fact that the new measurements apply to the picture grade judgments of nonexpert viewers whereas the SJM results were based largely on the more-critical judgments of expert viewers. Moreover, the new measurements used "off-the-air" pictures with considerable subject motion to modulate both the wanted and unwanted signals, while the SJM formula was based for the most part on the use of a stationary picture (slide) for the signal. Finally, Ref. 41 estimates that use of the protection ratios given by Eq. (32) would result in just perceptible interference during less than 5 percent of possible program picture content. Considering all these factors, it seems safe to conclude that Eq. (32) is unnecessarily conservative for use in planning for the kinds of pictures and viewers likely to be encountered in operating systems.

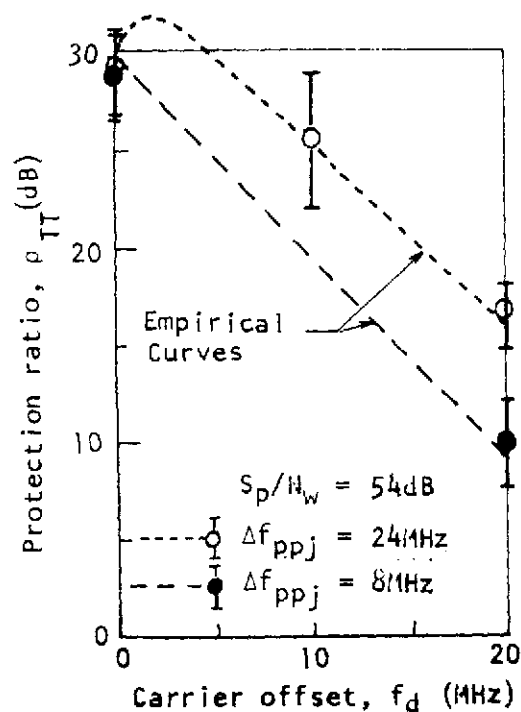
The CCIR has recently taken steps toward standardizing methods of protection-ratio measurement and interpretation^(38,42) so that the results of future experiments will be free of some of the difficulties just described. For this report, however, protection ratios will be represented by empirical equations that fit the available data for barely perceptible interference to a stationary picture whose picture-signal-to-weighted noise ratio lies between 50 and 54 dB--a noise level that produces no subjective picture degradation.

When both the wanted and the unwanted signal are TV/FM signals, the experimental data^(42,43) for 525-line systems shown in Fig. 10 can be fitted reasonably well by the following equation⁽²²⁾

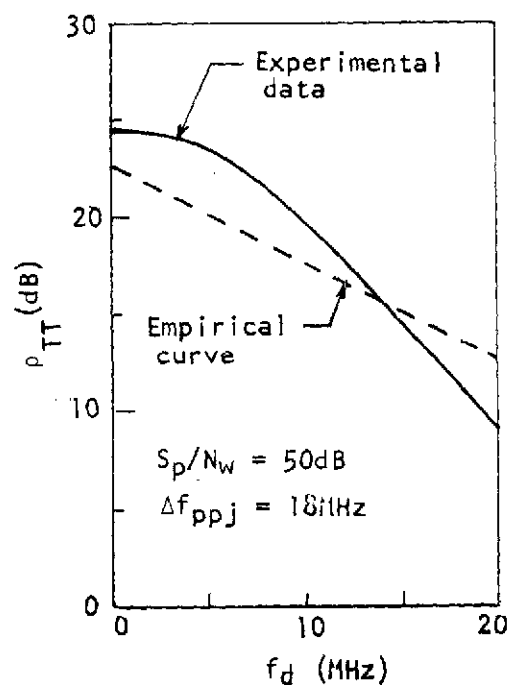
$$10 \log \rho_{TT}(M_1, M_j, f_d) = 29.5 - 20 \log M_1 - f_d M_1^{-0.85} - 0.475 \mu^{-2.5} f_d^{0.645} \mu \log \mu \quad (33)$$

where

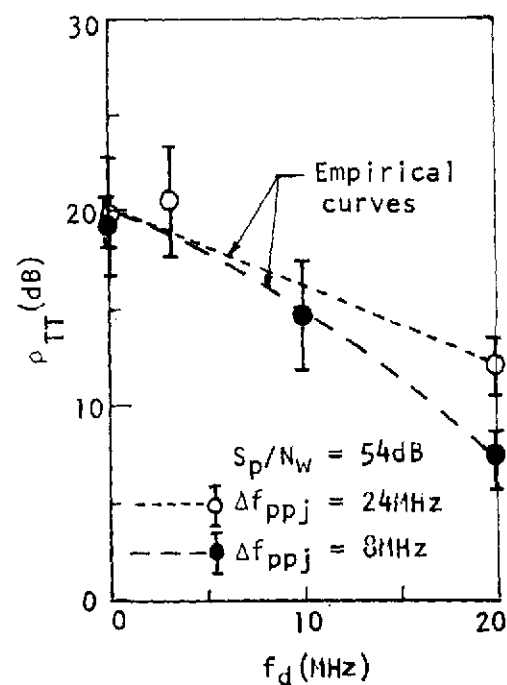
$$\mu = M_1/M_j$$



a. Wanted signal peak-to-peak frequency deviation $\Delta f_{ppi} = 8\text{MHz}$



b. Same as a. except $\Delta f_{ppi} = 18\text{MHz}$



c. Same as a. except $\Delta f_{ppi} = 24\text{MHz}$

Note: The vertical lines on the data points indicate the standard deviation of the measurements.

Fig. 10--Protection ratios for barely perceptible interference between two TV/FM signals

$$M_k = W_k / (2 f_{vk}) - 1 = \Delta f_{ppk} / (2 f_{vk}) \quad (34)$$

= peak modulation index of the TV/FM signal on link k

W_k = Carson's-rule bandwidth of the TV/FM signal on link k

Δf_{ppk} = peak-to-peak deviation caused by television baseband signal (including synchronizing pulses) on link k

f_{vk} = maximum frequency of video signal on link k

= 4.2 MHz for the U.S. 525-line television signal

Plots of Eq. (33) for the combinations of wanted and unwanted signal represented by the experimental measurements are shown by the dashed lines in Fig. 10. It will be noted that at worst ($f_d = 5$ MHz for $\Delta f_{pp} = 18$ MHz), the value predicted by Eq. (33), is 3 dB low and in all other cases, the predicted values are well within the standard deviation of the measurements.

Comparing Eq. (33) with the SJM formula given by Eq. (32), it is seen that the protection ratios predicted by Eq. (33) with $f_d = 0$ (the only value to which Eq. (32) applies) are consistently about 6 dB lower. Since both formulas are based on measurements with wanted signals modulated by a stationary picture and having output signal-to-weighted noise ratios of 49 dB or greater, the difference is probably attributable to the previously noted fact that the SJM formula was adjusted to yield protection ratios so high that, for 95 percent of possible program picture content, interference effects would not be even barely visible. The protection ratios to make interference invisible for 70 percent of the possible pictures were estimated by the SJM to be 4 or 5 dB lower. Consequently, the use in this report of protection ratios based on Eq. (33) may be regarded as equivalent to the use of the SJM formula but with interference rendered invisible for, say, 65 percent of the time rather than 95 percent.

On the other hand, Eq. (33) makes no allowance for the interference-masking effects of noise. In this connection it might be noted that Eqs. (32) and (33) yield virtually identical results for a picture with a 43 dB signal-to-weighted noise ratio. If desired,

a term $49 - 10 \log (S_p/N_w)$ can be added to Eq. (33) for the case of wanted signals with output signal-to-noise ratios lower than 49 dB.

All of these questions are academic, however, so far as the sensitivity factor Q_{TT} is concerned. Its value reflects only differences in protection ratio caused by differences in the modulation indices and the carrier frequencies of the wanted and unwanted signals.

Thus, substituting Eq. (33) into Eq. (31), the sensitivity factor for interference between two TV/FM signals is independent of the absolute value of the protection ratio for co-channel interference

$$10 \log Q_{TT} = f_d M_i^{-0.85} + 0.475 \mu^{-2.5} f_d^{0.645} \mu \log \mu \quad (35)$$

When the unwanted FM signal carries FDM telephony, the sensitivity factor is defined as

$$Q_{ij} = Q_{TF}(M_i, M_j, f_d) = \rho_{TT}(M_i, M_i, 0) / \rho_{TF}(M_i, M_j, f_d) \quad (36)$$

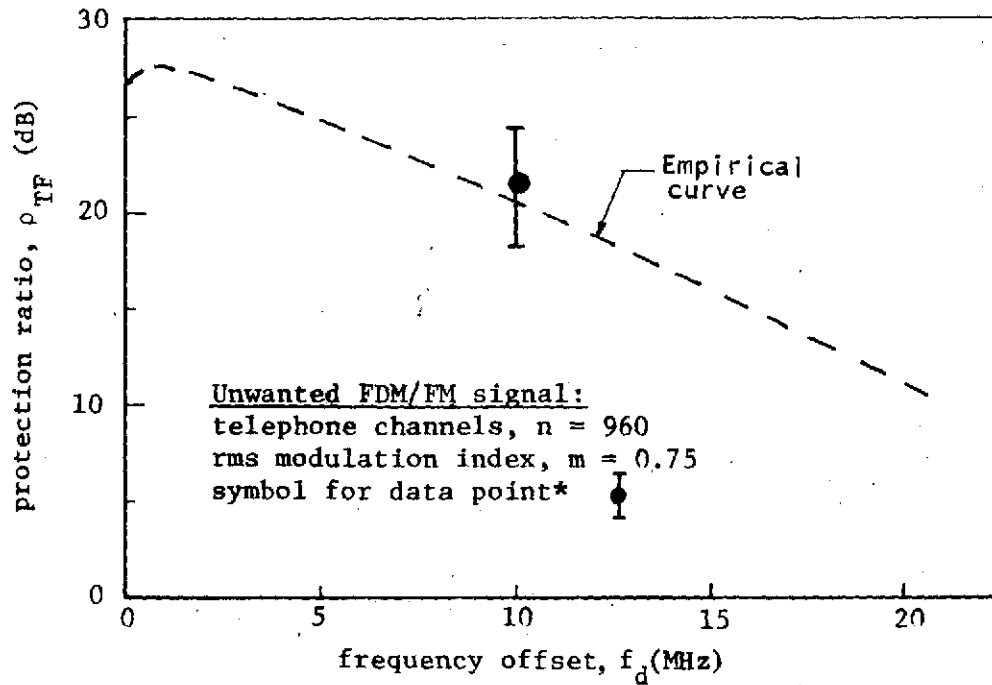
where ρ_{TT} is given by Eq. (33) and $\rho_{TF}(M_i, M_j, f_d)$ is the protection ratio for barely perceptible interference to a TV/FM signal with peak modulation index M_i and carrier frequency f_i from an FDM/FM signal with an effective peak modulation index M_j and a carrier frequency $f_j = f_i + f_d$.

An empirical fit⁽²²⁾ to the available experimental data,⁽⁴³⁾ shown in Fig. 11, gives

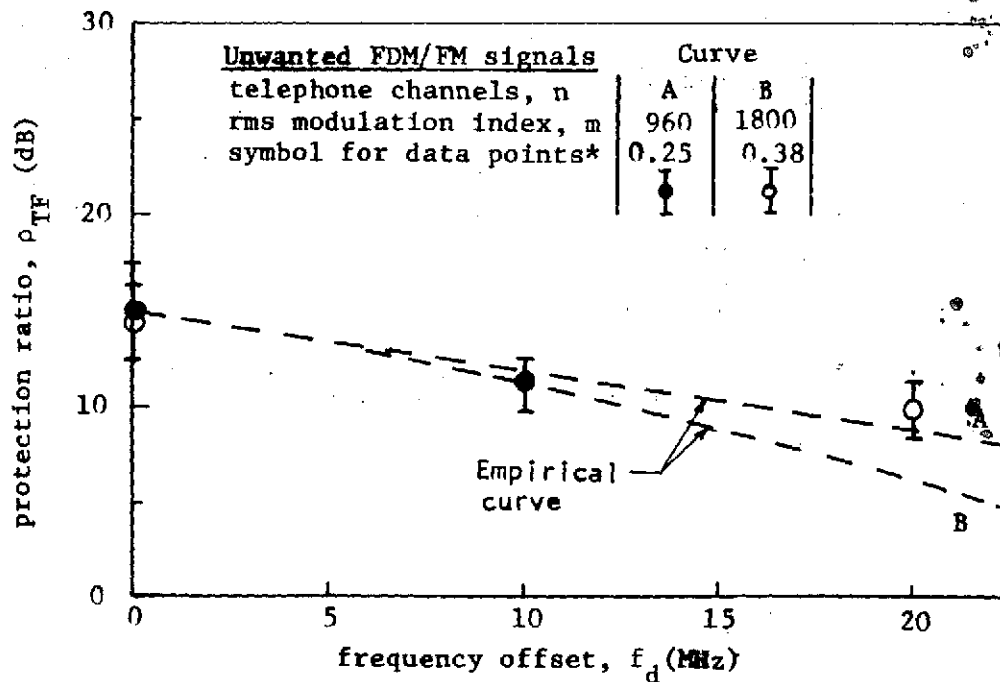
$$\begin{aligned} 10 \log \rho_{TF}(M_i, M_j, f_d) = & 24.1 - 20 \log M_i - f_d M_i^{-1.15} \\ & - 0.85 \mu^{-3} f_d^{0.5} \mu \log \mu \end{aligned} \quad (37)$$

where

$$\mu = M_i / M_j \quad (38)$$



a. Peak-to-peak deviation of wanted TV/FM signal 8 MHz



b. Peak-to-peak deviation of wanted TV/FM signal 24MHz

*Note: Vertical lines on data points indicate standard deviation

Fig. 11--Protection ratios for barely perceptible interference to a TV/FM signal from an FDM/FM signal

M_i = peak modulation index of the wanted TV signal

$$M'_j = \left(\frac{W_j}{2f_{mj}} - 1 \right) \left(\frac{f_{mj}}{f_{mi}} \right)^{1.5} \quad (39)$$

= equivalent peak modulation index of the unwanted FDM/FM signal

The second factor in Eq. (39) adjusts the actual peak modulation index given by the first factor to a value that improves the agreement of Eq. (37) with the experimental data.* Substituting Eqs. (33) and (37) into Eq. (36) yields the sensitivity factor for interference to a TV/FM signal from an FDM/FM signal.

$$10 \log Q_{TF} = 5.4 + f_d M_i^{-1.15} + 0.85 \mu^{-3} f_d^{0.5} \mu \log \mu \quad (40)$$

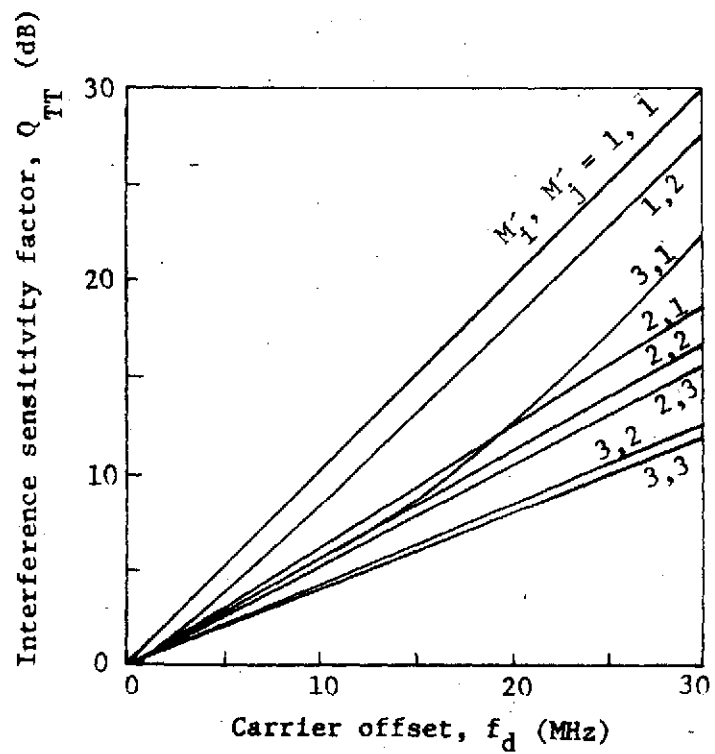
Plots of Q_{TT} and Q_{TF} versus f_d are given in Fig. 12. Note that in no case does the interference sensitivity depend on the modulation index of the unwanted signal when the carrier-frequency offset is zero. Also note that, for zero-frequency offset, a TV/FM signal is over 5 dB less susceptible to interference from an FDM/FM signal than to interference from another TV/FM signal.

UNWANTED-TO-WANTED RF SIGNAL RATIOS

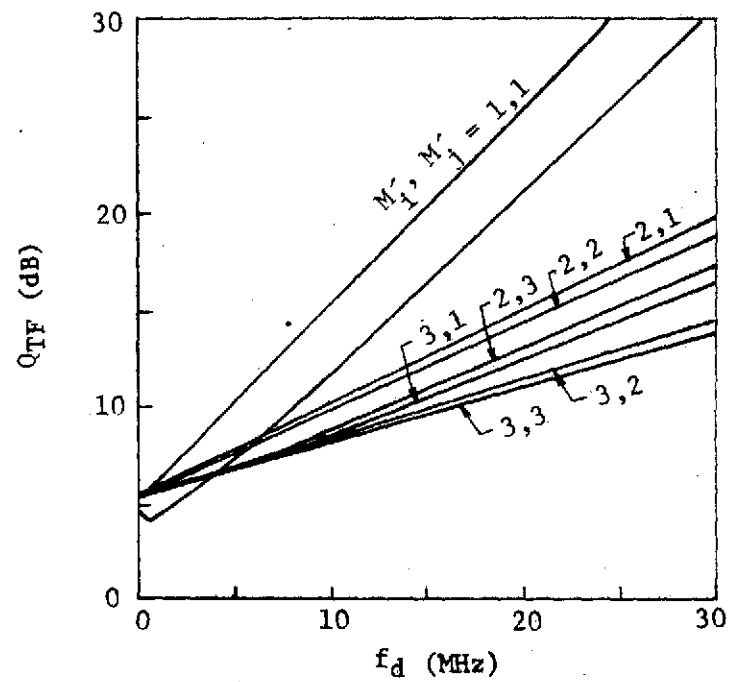
Considering either uplinks or downlinks, the ratio of unwanted-to-wanted signal power involved in the interference from link j to link i may be written

$$\frac{X_{ij}}{C_i} = \frac{S_{ij}}{S_{ii}} \quad (41)$$

* Personal communication from M. C. Jeruchim, General Electric Space Systems Organization, Valley Forge Space Center, Valley Forge, Pennsylvania, 1973.



a. TV/FM unwanted signal



b. FDM/FM unwanted signal

Fig. 12--Interference sensitivity of a TV/FM signal

where S_{ij} is a general expression for the signal power produced at the link i receiver input by the link j transmitter. In terms of the relevant hardware and propagation parameters

$$S_{ij} = P_j \Pi_{ij} / L_{ij} \quad (42)$$

where

- P_j = output power of link j transmitter
- Π_{ij} = product of gains of link j transmitting antenna and link i receiving antenna in directions along the transmission path between them
- L_{ij} = transmission path loss

Thus, determination of the individual unwanted-to-wanted signal ratios reduces to calculation of the antenna gain products and path losses for all of the wanted and unwanted signal paths. Certain general aspects of these calculations will be discussed in this subsection; the equations for specific antenna patterns, for path loss variations, and for calculating path lengths and antenna pointing angles will then be treated in separate subsections.

Antenna Gain Products

In computing the antenna gain products Π_{ij} that appear in the expression for S_{ij} , it must be recognized that, although an antenna may be described as being either horizontally or vertically polarized, this is only an idealization. In practice, a horizontally polarized transmitting antenna will in fact emit some vertically polarized radiation, and a vertically polarized receiving antenna will accept some horizontally polarized radiation--the relative amount increasing with angle from the antenna axis. Thus, in addition to the conventional antenna pattern $G(\varphi)$ which shows the angular sensitivity in a specified plane through the antenna axis to radiation of the polarization for which it was designed, there is a pattern $G(\varphi)$ showing its output of,

or response to, radiation of the opposite, or cross, polarization. The ratio of these two patterns at a given angle from the antenna axis is the "polarization discrimination"

$$\delta(\varphi) = G^+(\varphi) / G^-(\varphi) \quad (43)$$

at that angle.

Both $G^+(\varphi)$ and $G^-(\varphi)$ will show a lobe structure for off-axis angles outside the main lobe. The general dependence of the envelope of the sidelobe peaks on off-axis angle is sketched in Fig. 13a for both the co-polarized and the cross-polarized antenna patterns. The corresponding polarization discrimination dependence is shown in Fig. 13b.

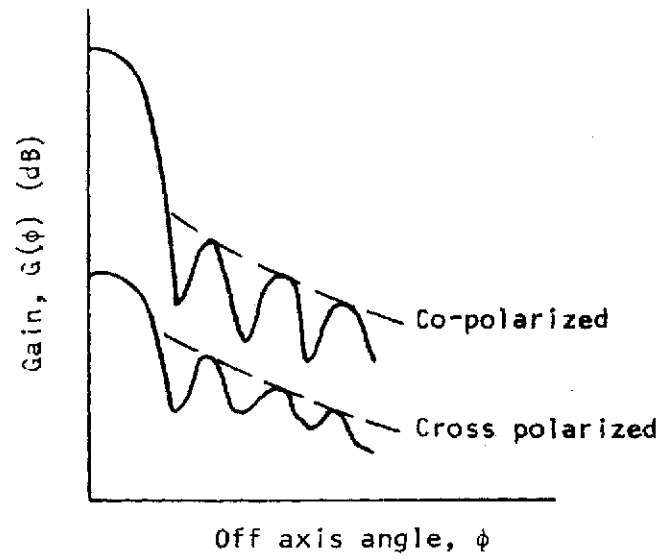
In terms of the co-polarized and cross-polarized antenna patterns, there are two expressions for the gain product, depending on whether the transmitting and receiving antennas have the same or opposite polarizations*

$$\Pi_{ij} = \begin{cases} \Pi_{ij}^+(\varphi_1, \varphi_2) = G_j^+(\varphi) G_i^+(\varphi_2) + G_j^-(\varphi) G_i^-(\varphi_2) & (44a) \\ \Pi_{ij}^-(\varphi_1, \varphi_2) = G_j^+(\varphi_1) G_i^-(\varphi_2) + G_j^-(\varphi_1) G_i^+(\varphi_2) & (44b) \end{cases}$$

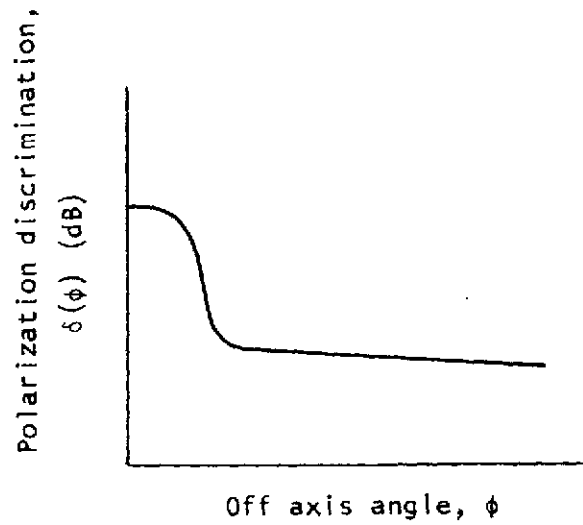
$$+ \sin^2 \epsilon G_j^+(\varphi_1) G_i^+(\varphi_2)$$

where φ_1 is the angle between the axis of the link j transmitting antenna and the path to the link i receiving antenna, φ_2 is the angle between the axis of the link i receiving antenna and the path from the link j transmitting antenna, and ϵ is the angular misalignment of the polarization axes. The superscript + or - on Π indicates that the wanted (ith) link and the unwanted (jth) link have the same or opposite polarizations, respectively.

*The expressions in Eq. (44) correspond to adding the rms values of the voltages at the antenna terminals associated with the terms in the sum since these voltages will not normally be in phase.



a. Gain patterns and envelopes



b. Polarization discrimination

Fig. 13--General behavior of co-polarized and cross-polarized antenna patterns

In the expression for Π_{ij}^+ the second term will always be negligible compared with the first. In the case of Π_{ij}^- , the first or the second term will normally be much larger than the others, but their relative magnitudes will depend on the beamwidths of the two antennas involved and the relative sizes of the off-axis angles ϕ_1 and ϕ_2 . Note that for small ϵ , the third term in Eq. (44b) may be approximated by $\epsilon^2 \Pi_{ij}^+$.

Path Losses

For frequencies below 10 GHz, the path loss displays only comparatively small departures from its free space value

$$L_{oij} = (4\pi a_{ij} / \lambda_i)^2 \quad (45)$$

where

- $\lambda_i = 0.3 f_i$
= wavelength of carrier on link i (m)
- f_i = carrier frequency on link i (GHz)
- a_{ij} = path length from link j transmitting antenna to
link i receiving antenna (m)

Above 10 GHz, absorption and scatter by rain can cause the path loss to exceed its free space value by larger amounts, which depend on the nature and density of the rain and on the length of path affected. The fraction of time that the loss on a given earth-space path exceeds a specified value thus depends on the rainfall characteristics in the vicinity of the earth-station location and on the elevation angle of the satellite.

Measurements have been made for frequencies of 15.3 GHz and 31.65 GHz at a number of earth-station locations to determine directly the rainfall attenuation statistics for earth-to-space paths, and also the correlation of these statistics with various meteorological and radiometric descriptions of rainfall. ⁽⁴⁴⁾ Although additional data

are needed for other frequencies and locations, it is possible to extrapolate the experimental results as was done in Fig. 6 to obtain reasonable estimates for the ratio

$$M_{ij}(p) = L_{ij}(p)/L_{oij} \quad (46)$$

of total path loss exceeded only during some small percentage of the time p to the free-space path loss for a path described by the location of its earth station and the elevation angle of its space station.

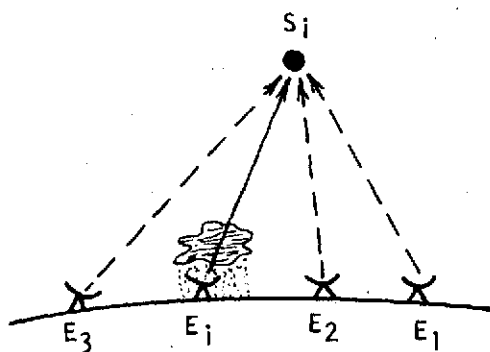
The approximate effect of rain attenuation on message quality for a wanted link i can then be expressed in terms of the distribution $M_{ij}(p)$ using the following argument. Suppose that link i carries FDM telephony and that in clear weather the total interference noise calculated by Eq. (22) is

$$I_i^C = I_{up}^C + I_{down}^C = (1 + k)I_{up}^C \quad (47)$$

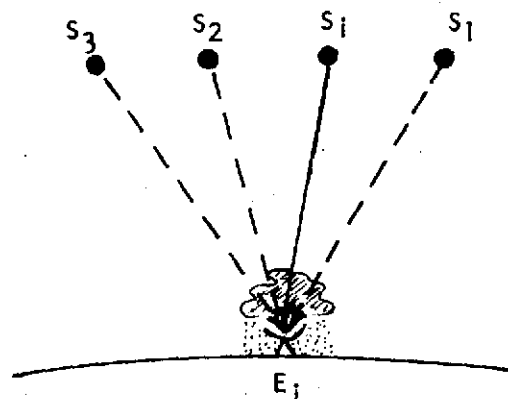
where I_{up}^C and I_{down}^C are, respectively, the total clear-weather uplink and downlink interference noise contributions and k is the ratio of the latter to the former.* Because circuit outages can be tolerated for only small percentages of the time, interest centers on very small values of p . The path losses exceeded for these values of p are usually caused by intense, but localized, rainfall which will normally affect only a single earth station at a time.

Referring to the sketches in Fig. 14, it is seen that link i will suffer serious message degradation only when localized rainfall envelops its uplink earth station. This attenuates the uplink wanted signal C_i without affecting the unwanted uplink signals X_{ij} . In particular, the uplink interference noise which is exceeded only p percent of the time because of rainfall is

*An exactly similar argument applies for TV links if I is replaced by $\Sigma X/(CQ)$.



a. Uplink paths



b. Downlink paths

Note : Wanted signal paths are shown by solid lines,
unwanted signal paths by dashed lines.

Fig. 14--Path geometry during heavy localized rainfall

$$I_{up}^r = M_{ii}(p) I_{up}^c$$

The effect of localized rain at the downlink earth station on link i will usually be to attenuate both wanted and unwanted signals about equally so that the downlink noise during intense rainfall differs but little from its clear-space value

$$I_{down}^r = I_{down}^c$$

Using Eq. (47), it follows that the ratio of the total interference noise exceeded a small percentage of the time p because of rainfall on link i to the total interference experienced in clear weather is approximately

$$\frac{I_i^r(p)}{I_i^c} = \frac{M_{ii}(p) + k}{1 + k} \quad (48)$$

For example, if the downlink noise on link i is four times the uplink noise in clear weather ($k = 4$), and if $M_{ii}(p) = 10$, then the total interference noise will exceed its clear-sky value by a factor of 2.8(4.5 dB) only p percent of the time.

Link performance objectives normally take into account the expected signal fading caused by variable path losses by specifying the percentages of time that various levels of interference noise can be exceeded. The question then is whether the actual interference performance described by substituting experimental values of $M_{ii}(p)$ into Eq. (48) is better or worse than that called for by the link performance objectives. If it is better than specifications, even for the links subject to the most severe rain attenuation, then the effects of rain on interference performance can be ignored.

Referring to Fig. 4a and assuming that the objective for interference from other satellite systems varies with percentage of time in the same fashion as the CCIR objective for interference from

terrestrial systems, the allowable interference relative to its clear-weather value will vary as shown by the dashed curve in Fig. 15. Then, applying Eq. (48) to the expected attenuation for Miami shown in Fig. 7, the expected total interference relative to its clear-weather value will vary as shown for several values of k by the solid curves of Fig. 15. Since even for equal clear-weather uplink and downlink interference ($k = 1$), the expected interference in the "worst-case" rainfall area of Miami is less than the CCIR objective, it is concluded that system design can safely be based on clear-weather interference performance.

ANTENNA PATTERNS

To compute the antenna gain products defined in connection with Eq. (42), equations are needed for the co-polarized and cross-polarized patterns of antennas typical of those likely to be used in the 12 GHz band by fixed- and broadcasting-satellite systems. Co-polarized patterns for the main lobe and for the envelope of the sidelobes will be given first for antennas whose patterns are the same in any axial plane; i.e., whose beams have a circular cross section. The cross-polarized patterns of such antennas will then be discussed, and finally both types of pattern will be generalized to the case of antennas whose beams have an elliptical cross section.

Co-Polarized Main-Lobe Pattern for Circular Beams

The empirical pattern developed by Rice⁽⁴⁵⁾ will be used to represent the co-polarized main-lobe response of all antennas with circular beams, both earth station and satellite, in both fixed-satellite and broadcasting-satellite systems. The equation for the main-lobe segment of the Rice pattern is

$$G_o^+(\varphi) = G_o^+ \left[0.9976 \left(\frac{\sin u}{u} \right)^{2.25} + 0.0024 \right] \quad (49)$$

where G_o^+ is the co-polarized on-axis (or maximum) gain

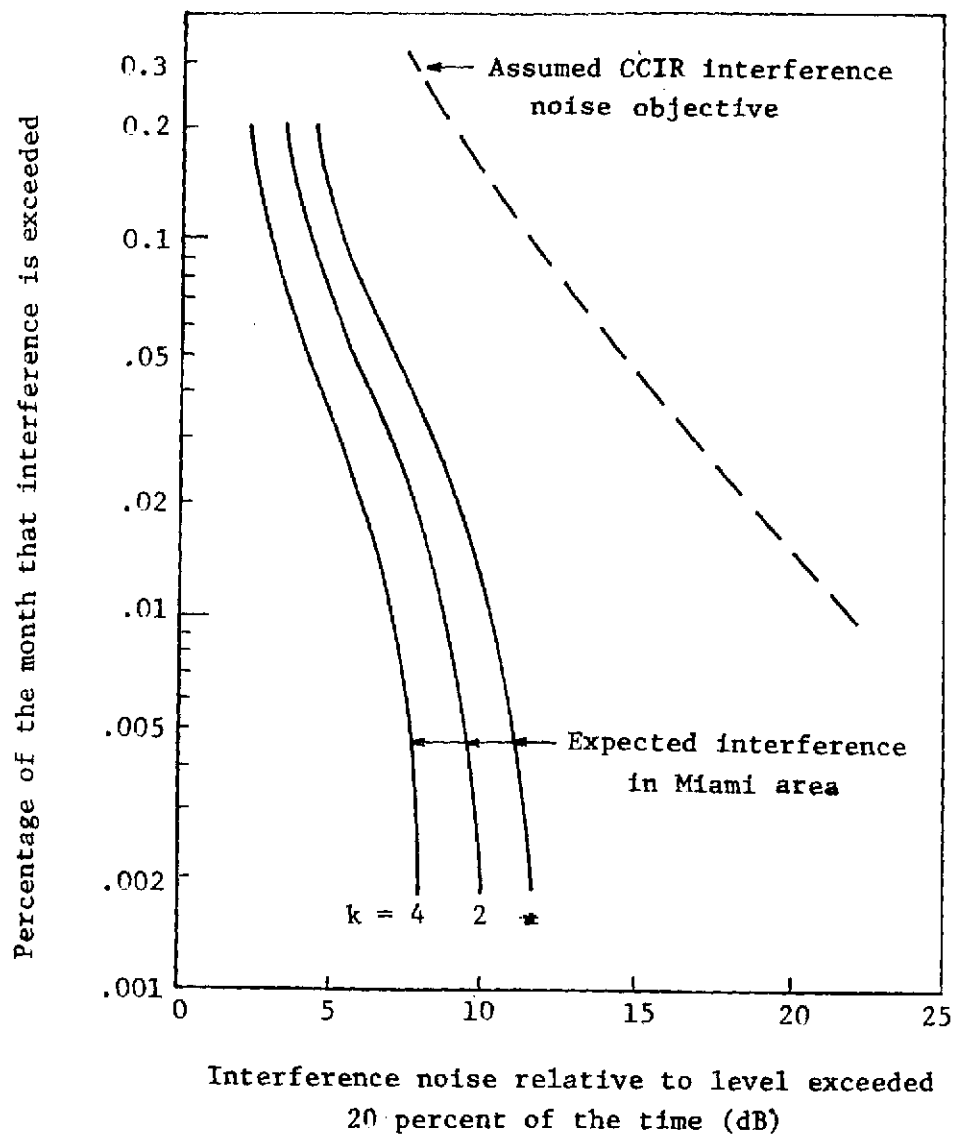


Fig. 15--Comparison of worst expected interference at 12 GHz with CCIR interference objectives

$$G_o^+ = \eta \left(\frac{\pi D}{\lambda} \right)^2 \quad (50)$$

and

$$u = \sqrt{G_o^+} \sin \varphi = \sqrt{\eta} \left(\frac{\pi D}{\lambda} \right) \sin \varphi \quad (51)$$

In these equations,

η = antenna efficiency

D = reflector diameter

λ = wavelength

The gain specified by Eq. (49) drops to one-half its maximum value when $u = 1.319$ radians. The implied half-power beamwidth (HPBW) is thus

$$\varphi_o = 2 \arcsin \frac{1.319}{\sqrt{\eta} \pi D / \lambda} \quad (\text{radians})$$

For the values of D/λ typical of the systems to be considered here, a good approximation to this value is

$$\varphi_o \approx \frac{48 / \sqrt{\eta}}{D/\lambda} \quad (\text{degrees}) \quad (52)$$

For example, with $\eta = 0.55$, $\varphi_o = 65 / (D/\lambda)$ degrees.

Illustrations of the relationships between D , G_o^+ , D/λ , and φ_o when $\eta = 0.55$ are given in Fig. 16 for $f = 11.7$ and 14 GHz.

Co-Polarized Sidelobe Envelopes for Circular Earth-Station Antennas

The CCIR has suggested specific equations to represent the envelope of sidelobe peaks in interference calculations involving earth-station antennas. The equations given for the fixed-satellite

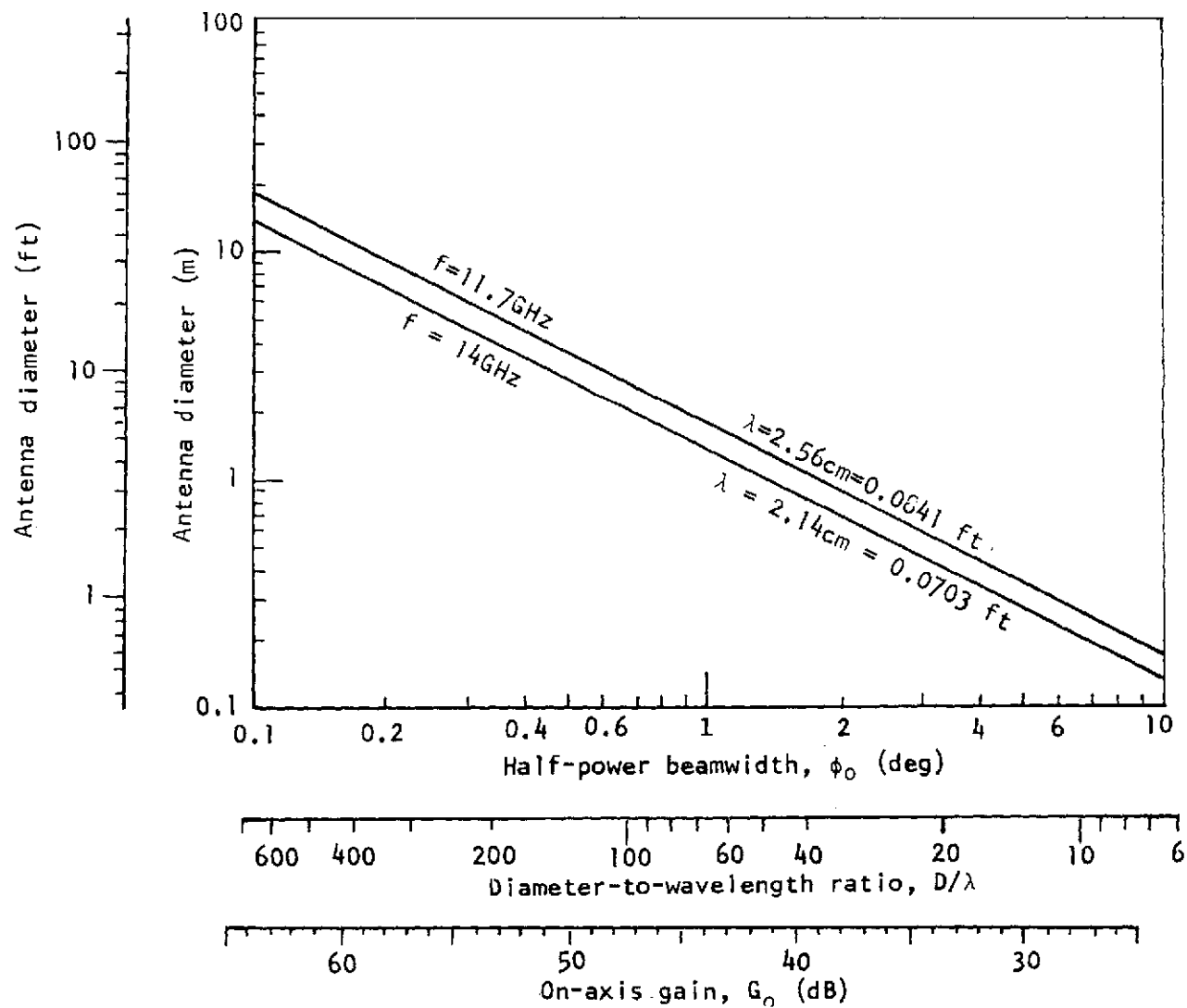


Fig. 16--Parameter relationships for circular parabolic antennas

service differ somewhat from those suggested for the broadcasting service. For the fixed-satellite service, the formula to be used depends on the diameter-to-wavelength ratio, D/λ , as follows^(46,47)

$$10 \log G^+(\varphi) = \max \begin{cases} 32-25 \log \varphi, \\ -10, \end{cases} \quad \frac{D}{\lambda} \geq 100 \quad (53a)$$

$$10 \log G^+(\varphi) = \max \begin{cases} 52-10 \log (D/\lambda)-25 \log \varphi, \\ -10, \end{cases} \quad \frac{D}{\lambda} < 100 \quad (53b)$$

where φ is the off-axis angle in degrees. For $D/\lambda = 100$, of course, the two equations yield the same value for $G^+(\varphi)$.

The equations representing sidelobe envelopes for receiving earth stations in the broadcasting-satellite service* depend on whether the station is used for individual reception or community reception.⁽⁴⁾ These equations differ from those of the fixed service, not only in the sidelobe performance assumed, but also in the quantities used; off-axis angle is expressed relative to the HPBW φ_0 , and gain is given in terms of the angular discrimination** in dB

$$g^+(\varphi) = 10 \log [G_o^+/G^+(\varphi)] \quad (54)$$

The pattern for community reception is

$$g^+(\varphi) = \min \begin{cases} 10.5 + 25 \log (\varphi/\varphi_0) \\ 10 \log G_o^+ \end{cases} \quad (55)$$

*There are no transmitting earth stations in the broadcasting-satellite service, since, by definition, the uplink to a broadcasting satellite is considered to be in the fixed-satellite service.

**Also called "relative gain" or "directivity."

and the pattern for individual reception is

$$G(\varphi)^+ = \min \begin{cases} 9 + 20 \log (\varphi/\varphi_0) \\ 10 \log G_0^+ \\ 30 \end{cases} \quad (56)$$

To compare the sidelobe performance assumed for the two services, the fixed-satellite service patterns can be put in the same form as Eqs. (55) and (56) by using Eqs. (50) and (52) to obtain

$$10 \log G_0^+ = 43.5 - 20 \log \varphi_0 \quad (57)$$

$$20 \log (D/\lambda) = (16.8 - 5 \log \eta) - 10 \log \varphi_0 \quad (58)$$

and substituting these expressions into Eqs. (53a) and (53b). The result, corresponding to an assumed antenna efficiency of about 57 percent, is

$$g(\varphi)^+ = \min \begin{cases} 11.5 + 5 \log \varphi_0 + 25 \log \frac{\varphi}{\varphi_0} \\ 10 \log G_0^+ + 10 \end{cases} \quad \frac{D}{\lambda} \leq 100 \quad (59)$$

$$g(\varphi)^+ = \min \begin{cases} 9.5 - 5 \log \varphi_0 + 25 \log \frac{\varphi}{\varphi_0} \\ 10 \log G_0^+ + 10 \end{cases} \quad \frac{D}{\lambda} < 100 \quad (60)$$

Plots of the earth-station pattern envelopes given by Eqs. (55), (56), (59), and (60) are shown for a given number of values of D/λ in Fig. 17. It is seen first of all that, while all of the patterns except for broadcasting satellite, individual reception, vary with off-axis angle at the same rate, the discrimination $g(\varphi)^+$ assumed for broadcasting-satellite, community reception, antennas is a few dB superior to that assumed for most sizes of fixed-satellite antennas in the near sidelobes, and 10 dB inferior (for a given D/λ) in the far sidelobe region. At $D/\lambda = 116$ and 86, the near sidelobe

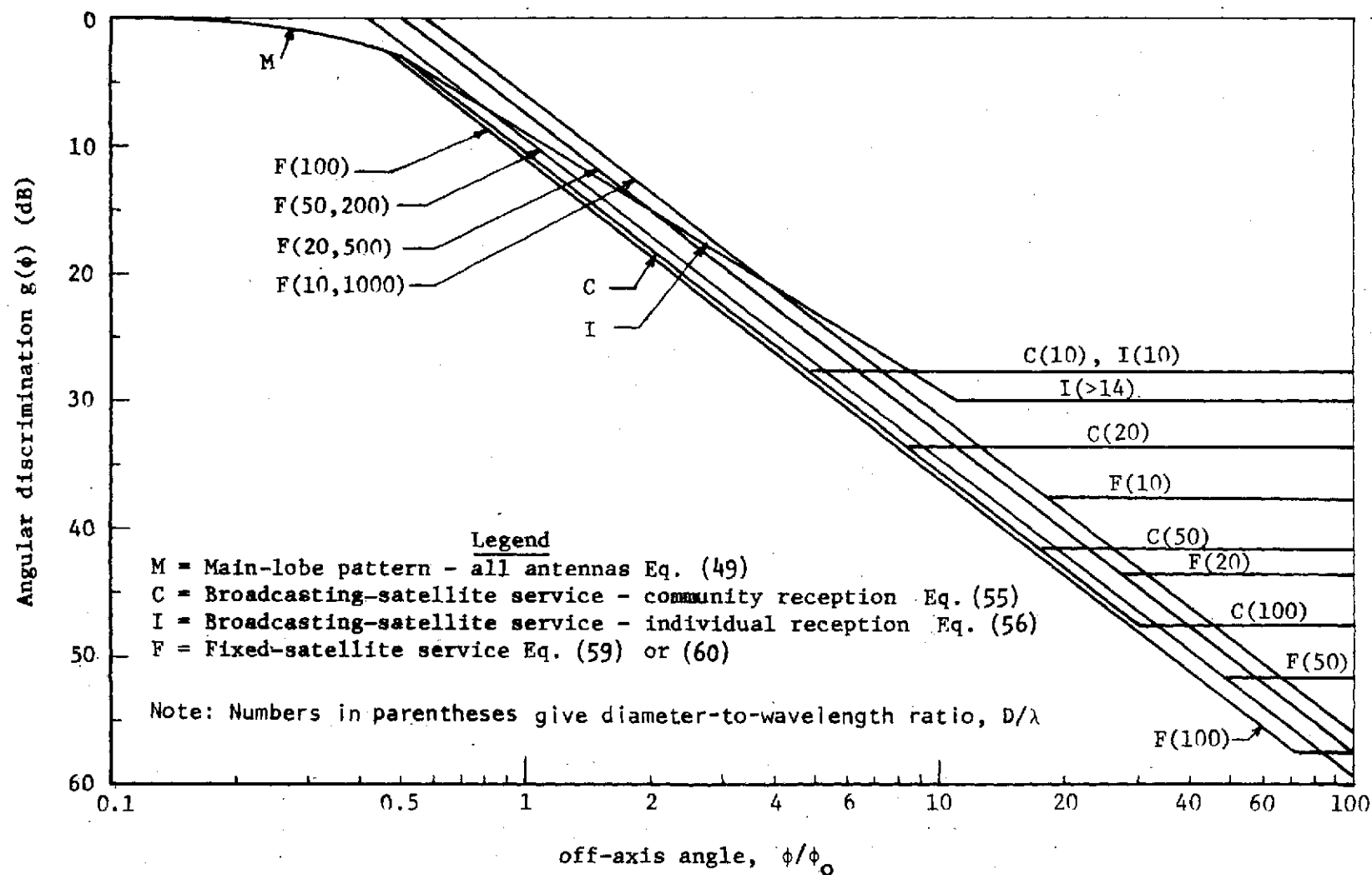


Fig. 17--Earth station antenna pattern envelopes

performance is the same for the two services. The last difference corresponds to the fact that, in the far sidelobes, the gain of the broadcasting-satellite receiving antennas is taken at approximately the isotropic level, whereas for fixed-satellite earth stations, the gain is expected to be kept at least 10 dB below this level.

Another feature of the patterns for the fixed-satellite service displayed in Fig. 17 is that the angular discrimination of any two antennas whose values of D/λ are such that their product equals 10^4 (for example, $D/\lambda = 50$ and $D/\lambda = 200$), are represented by the same line in the near sidelobe region, although the discrimination in the far sidelobes will of course be larger for the larger antenna.

Co-Polarized Sidelobe Envelopes for Circular Satellite Antennas

Just as with earth stations, the CCIR recommended sidelobe envelope for a satellite antenna depends on the service in question. The pattern tentatively proposed for the fixed-satellite service is given by⁽⁴⁸⁾

$$g(\varphi) = \begin{cases} 12(\varphi/\varphi_0)^2, & 0.5 \leq \varphi/\varphi_0 < 1.291 \\ 20, & 1.291 \leq \varphi/\varphi_0 < 3.1623 \\ 7.5 + 25 \log (\varphi/\varphi_0), & 3.1623 \leq \varphi/\varphi_0 < x \\ 10 \log G_0^+ + 10, & \varphi/\varphi_0 \geq x \end{cases} \quad (61)$$

where x is the value of φ/φ_0 for which $G(\varphi) = 0.1$. This pattern assumes that the antenna has been designed to maintain the first sidelobe level at least 20 dB below the main lobe.

The CCIR provides three patterns for satellite antennas in the broadcasting-satellite service, corresponding to the degree of design control maintained over the levels of the first few sidelobes.⁽⁴⁹⁾ If there is no sidelobe control, the assumed envelope is

$$g(\varphi) = \min \begin{cases} 10.5 + 25 \log (\varphi/\varphi_0) \\ 10 \log G_0^+ \end{cases} \quad (62)$$

With normal sidelobe control, it is assumed that the first sidelobes are held to a level 25 dB below the main lobe

$$g(\varphi) = \min \left\{ \begin{array}{ll} 10.5 + 25 \log (\varphi/\varphi_0), & 0.5 \leq \varphi/\varphi_0 < 0.8119 \\ 20 + 130 \log (\varphi/\varphi_0), & 0.8119 \leq \varphi/\varphi_0 < 1.0926 \\ 25, & 1.0926 \leq \varphi/\varphi_0 < 3.8019 \\ 7.5 + 25 \log (\varphi/\varphi_0), & \varphi/\varphi_0 > 3.8919 \\ 10 \log G_0^+, & \end{array} \right. \quad (63)$$

Finally, an envelope intended to represent the limit of the state of the art in sidelobe control is given. The equation for this discrimination pattern is formally identical to Eq. (63) except that the segment of constant discrimination occurs over the angular range $1.427 \leq \varphi/\varphi_0 < 15.11$, and the value of discrimination in this range is 40 dB rather than 25 dB.

Plots of the CCIR satellite antenna sidelobe envelopes are shown in Fig. 18. Referring to this figure, it will be noted that, just as with the earth-station patterns, the broadcasting-satellite envelopes imply performance superior to the fixed-satellite service in the near sidelobes (3 dB better in this case) but 10 dB worse in the far sidelobes. However, in contrast with the earth-station case, it is not as likely that these differences will be reflected by the practical antennas actually used by the two services.

Transition Between Main-Lobe Pattern and Sidelobe Envelopes

The sidelobe envelope equations for all antennas in the broadcasting-satellite service and for satellite antennas in the fixed-satellite service are written to yield a discrimination of 3 dB when $\varphi = \varphi_0/2$. There is thus no discontinuity between the main-lobe pattern and the sidelobe envelope, and the latter can conservatively be used for $\varphi/\varphi_0 \geq 0.5$.

In the case of earth stations in the fixed-satellite service, however, the sidelobe envelopes given by Eqs. (53) and (54) or (59) and (60) fail to intersect the main-lobe pattern at any angle when D/λ is greater than about 135 or less than 74. In Ref. 22, where it

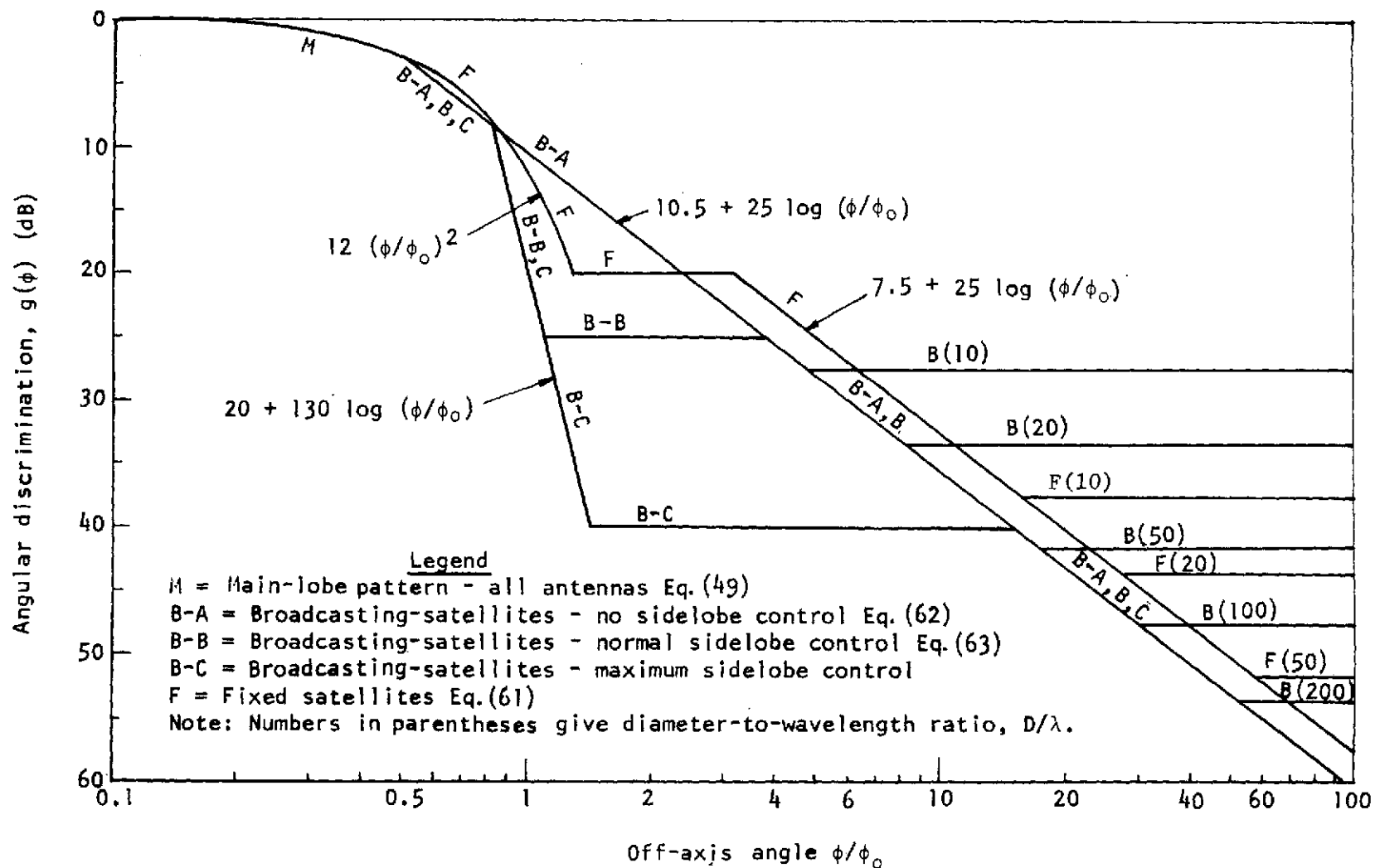


Fig. 18--Satellite antenna pattern envelopes

was erroneously asserted that the problem occurred for $D/\lambda \geq 175$, this anomaly was dealt with by assuming that the sidelobe envelope applied down to the value of φ/φ_0 for which the discrimination was zero, and that for off-axis angles smaller than this, the discrimination remained at zero. In this report, we make the more realistic assumption that, for earth stations in the fixed-satellite service, the discrimination in the main lobe out to $\varphi/\varphi_0 = 0.5$ is given by Eq. (49), and the discrimination in the sidelobes beyond $\varphi/\varphi_0 = 1.5$ by either Eq. (59) or (60). In the transition region, $0.5 < \varphi/\varphi_0 < 1.5$, it is assumed that the main-lobe and sidelobe patterns are connected by a curve that appears as a straight line on a plot of $g(\varphi)$ versus $\log(\varphi/\varphi_0)$.

Polarization Discrimination and Cross-Polarized Patterns

A new draft CCIR report on polarization discrimination by means of orthogonal circular and linear polarization⁽⁵⁰⁾ concludes that for satellite antennas, an overall polarization discrimination (including the effect of polarizers) of 25 to 35 dB for linear polarization and 25 to 30 dB for circular polarization is currently achievable within the half-power beamwidth ($\varphi/\varphi_0 \leq 0.5$).

The overall polarization discrimination currently achievable for earth-station antennas in the fixed-satellite service is a few dB smaller because of the need to maintain discrimination over both the transmission and reception bandwidths while carrying high microwave power levels and meeting the requirements of low-noise performance. The report estimates that, within the half-power beamwidth, a polarization discrimination of 25 dB for circular polarization and 20 dB for linear polarization can be maintained with present-day technology. With future developments, these values will increase by 5 dB, making the performance of earth-station antennas comparable to that of satellite antennas.

Less information is available concerning the polarization discrimination achievable outside the main beam, but an inspection of the experimental data presented in Ref. 50 for three antennas shows that the discrimination lies in the range from 10 to 15 dB at all off-axis angles less than 90 deg. For a given antenna, the discrimination appears to be constant within a few dB independent of angle,

whether measured as the difference between the actual co-polarized and cross-polarized patterns, or between their peak envelopes.

For purposes of interference prediction for future broadcasting- and fixed-satellite systems, the foregoing conclusions will be represented by one of two empirical equations for polarization discrimination as a function of normalized off-axis angle φ/φ_0 . The "best case," corresponding to a discrimination of 35 dB in the main lobe and 15 dB in the sidelobe region is given by

$$10 \log \delta(\varphi) = \begin{cases} 35, & \varphi/\varphi_0 \leq 0.393 \\ 46 - 28 \varphi/\varphi_0, & 0.393 < \varphi/\varphi_0 < 1.107 \\ 15, & \varphi/\varphi_0 \geq 1.107 \end{cases} \quad (64)$$

The "worst-case" alternative, which corresponds to 30 dB of discrimination in the main lobe and 10 dB in the sidelobes, is given by the same equation but with the constants in each of the three ranges of φ/φ_0 reduced by 5 dB. Plots of both equations are shown in Fig. 19.

Having selected the appropriate polarization discrimination pattern, the cross-polarized pattern $G(\varphi)$ for any antenna is readily calculated using the definition given in Eq. (43), viz

$$G(\varphi) = G^+(\varphi) / \delta(\varphi)$$

Patterns for Antennas with Beams of Elliptical Cross Section

Unless stated otherwise, it will be assumed that all earth-station antenna beams have circular cross sections. However, to better match the footprints of their antennas to the distribution of earth stations being served, many planned satellite antennas have elliptical beams. In this case, the antenna reflector is itself usually elliptical in shape and requires the specification of its major and minor axial dimensions, D_1 and D_2 , respectively.

The on-axis gain of such an antenna will be taken as the gain of an equivalent circular antenna having the same physical area

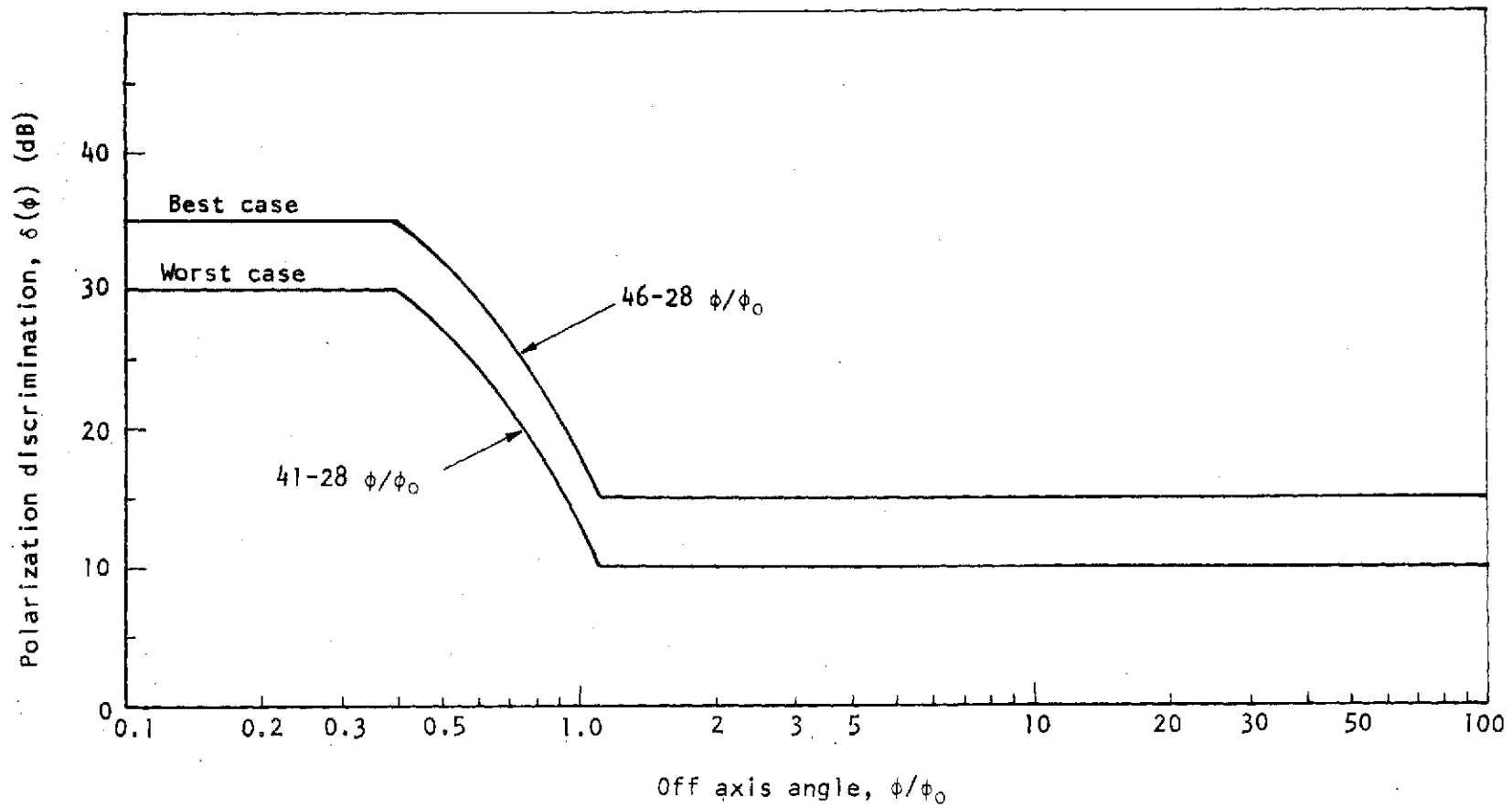


Fig. 19--Polarization discrimination

$$G_O^+ = \eta \pi^2 D_1 D_2 / \lambda^2 \quad (65)$$

To specify the pattern of the elliptical antenna in a plane through the antenna axis that intersects the reflector at an angle ψ from its minor axis, it is assumed that the directivity $g(\varphi)$ in that plane is the same as for a circular antenna with a diameter equal to the dimension $D(\psi)$ of the reflector in the plane.

Thus, the main-lobe pattern will be given by Eq. (49) with G_O^+ given by Eq. (65) instead of Eq. (50), and μ given by

$$\mu = \sqrt{\eta} \pi \frac{D(\psi)}{\lambda} \sin \varphi \quad (66)$$

instead of Eq. (61). And, since all of the sidelobe envelope equations involve only φ/φ_O , they may be used for the selected axial plane by computing φ_O from the "elliptical equivalent" of Eq. (62)

$$\varphi_O = \frac{48/\sqrt{\eta}}{D(\psi)/\lambda} \quad (67)$$

It remains to show how to compute the value of ψ corresponding to a particular interference geometry and, given ψ , how to compute $D(\psi)$ from D_1 and D_2 . The computation of ψ is a straightforward, albeit tedious, exercise in solid analytic geometry. Referring to the sketch in Fig. 20, it will be assumed that the elliptical satellite antenna is oriented so that the maximum dimension of its footprint lies along the line AF, where A is the antenna aim point (the intersection of the antenna axis with the earth) and F is a point on earth which specifies the desired footprint orientation. The maximum beamwidth plane Π_1 , determined by the antenna axis SA and the point F, intersects the antenna reflector along its minor axis and may thus be used as the reference for measuring ψ .

The axial plane Π_2 in which the pattern is desired is the one containing the path between the satellite S and the earth station E. Therefore, the angle ψ to be calculated is just the angle between the planes Π_1 and Π_2 . In terms of the direction numbers l_1, m_1, n_1 and

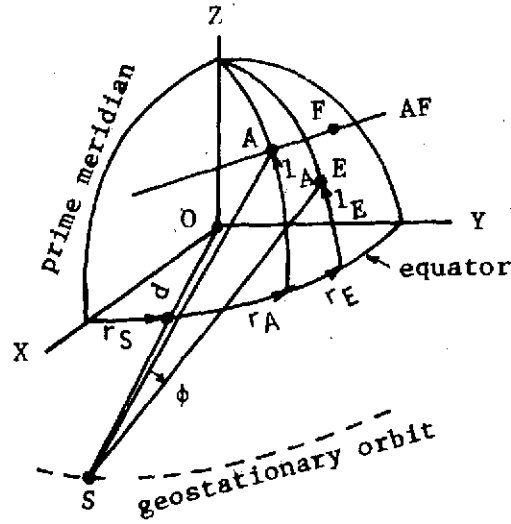


Fig. 20--Geometry for orientation of elliptical antennas and calculation of off-axis angles on space-earth paths

l_2, m_2, n_2 of the normals to the planes Π_1 and Π_2 , respectively,

$$\cos \psi = \frac{l_1 l_2 + m_1 m_2 + n_1 n_2}{\sqrt{(l_1^2 + m_1^2 + n_1^2)(l_2^2 + m_2^2 + n_2^2)}} \quad (68)$$

where the direction numbers are referred to the rectangular coordinate system shown in Fig. 20 with origin at the center of the earth, the Z axis through the north pole and the X axis through the prime meridian.

The direction numbers l_1, m_1, n_1 can be computed in terms of those for the intersecting lines SA and AF that define the plane Π_1 .

Similarly, l_2, m_2, n_2 can be computed from the direction numbers of the lines SA and SE that define Π_2 . Thus,

$$\Pi_1: \quad l_1 = b_1 c_3 - b_3 c_1, \quad m_1 = c_1 a_3 - c_3 a_1, \quad n_1 = a_1 b_3 - a_3 b_1$$

$$\Pi_2: \quad l_2 = b_1 c_2 - b_2 c_1, \quad m_2 = c_1 a_2 - c_2 a_1, \quad n_2 = a_1 b_2 - a_2 b_1$$

where the direction numbers of the three lines in question may be expressed as follows in terms of the x, y, z coordinates of the points S, A, E, and F

$$\text{SA: } a_1 = x_A - x_S \quad b_1 = y_A - y_S \quad c_1 = z_A - z_S$$

$$\text{SE: } a_2 = x_E - x_S \quad b_2 = y_E - y_S \quad c_2 = z_E - z_S$$

$$\text{AF: } a_3 = x_F - x_A \quad b_3 = y_F - y_A \quad c_3 = z_F - z_A$$

Expressing distances in units of the earth's radius, these coordinates are

$$\text{S: } x_S = d \cos r_S \quad y_S = d \sin r_S \quad z_S = 0$$

$$\text{A: } x_A = \cos l_A \cos r_A \quad y_A = \sin l_A \cos r_A \quad z_A = \sin l_A$$

$$\text{E: } x_E = \cos l_E \cos r_E \quad y_E = \sin l_E \cos r_E \quad z_E = \sin l_E$$

$$\text{F: } x_F = \cos l_F \cos r_F \quad y_F = \sin l_F \cos r_F \quad z_F = \sin l_F$$

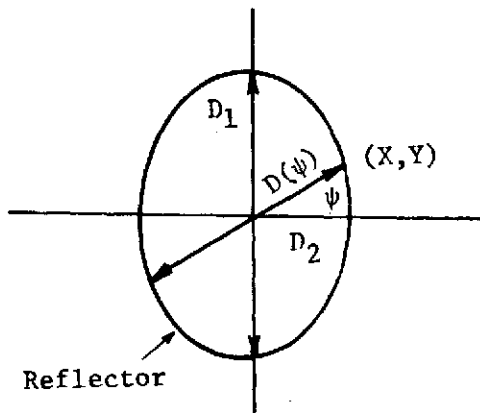
where $d = 6.617$ is the radius of the geostationary orbit, and l and r are, respectively, the latitude and longitude of the points whose subscripts they bear.

In the special case where it is desired that the long dimension of the antenna footprint be tangent to the parallel of latitude through the aim point, the direction numbers of AF reduce to

$$a_3 = -\sin r_A \quad b_3 = \cos r_A \quad c_3 = 0$$

The computation of $D(\psi)$ is much simpler. Referring to Fig. 21 and recalling that $D(\psi)$ is the "diameter" of the ellipse at an angle ψ from its minor axis, it follows directly from the equation of an ellipse in rectangular coordinates that

$$D(\psi) = (\sin^2 \psi / D_1^2 + \cos^2 \psi / D_2^2)^{-1/2} \quad (69)$$



$$\frac{x^2}{D_2^2/4} + \frac{y^2}{D_1^2/4} = 1$$

$$x = (1/2)D(\psi)\cos \psi$$

$$y = (1/2)D(\psi)\sin \psi$$

$$D(\psi) = \left(\frac{\cos^2 \psi}{D_2^2} + \frac{\sin^2 \psi}{D_1^2} \right)^{-1/2}$$

Fig. 21--Geometry for calculating "effective diameter" $D(\psi)$ of an elliptical antenna

TRANSMISSION PATH LENGTHS AND ANTENNA OFF-AXIS ANGLES

The path length between an earth station and a satellite is needed not only for calculating the free-space path loss defined in Eq. (44) but also for calculating the off-axis angles needed in the gain-product calculation of Eq. (43). Straightforward trigonometry applied to the triangle SOE in Fig. 20 yields for the path length a between a satellite S and an earth station E

$$a^2 = d^2 + 1 - 2d \cos l_E \cos (r_E - r_S) \quad (70)$$

where the symbols have the same meanings as before.

Again referring to Fig. 20, the off-axis angle φ_{SE} of the earth-station E viewed from the satellite S with antenna aimed at A is obtained by applying plane trigonometry to the triangle SAE,

$$\varphi_{SE} = \arccos \frac{a_1^2 + a_2^2 - p^2}{2a_1a_2} \quad (71)$$

where a_1 and a_2 are the path lengths SE and SA, and p is the straight line distance EA given by

$$p^2 = 2 \left[1 - \cos l_E \cos l_A \cos (r_E - r_A) + \sin l_E \sin l_A \right] \quad (72)$$

Finally, the off-axis angle φ_{ES} of a satellite S viewed from an earth-station E with antenna aimed at a point A at longitude r_A in the geostationary orbit is, by similar trigonometric arguments

$$\varphi_{ES} = \arccos \frac{a_1^2 + a_2^2 - s^2}{2a_1a_2} \quad (73)$$

where a_1 and a_2 are the path lengths ES and EA and s is the straight-line distance SA given by

$$s = 2d \sin \frac{1}{2}(r_S - r_A) \quad (74)$$

V. SHARING TACTICS AND METHODS FOR DETERMINING
COMPATIBLE SATELLITE SPACINGS

The preceding sections have laid the groundwork for designing fixed- and broadcasting-satellite systems to meet designated noise objectives and for computing the interference levels that will arise among such systems when a number of them share the orbit and spectrum. In this section, the interference equations of Sec. IV will first be analyzed to identify and assess the relative effectiveness of the various design tactics that reduce interference and thus can improve orbit-spectrum utilization. Parametric methods will then be described for determining the particular satellite system deployments that keep interference levels within specified objectives.

EQUATIONS FOR SINGLE INTERFERENCE ENTRIES

The basic constraint on any strategy for sharing the orbit and spectrum is that the total interference appearing at the message channel outputs in any sharing system shall not exceed specified limits. The general equations for computing the total interference in the worst channel of any rf link in a system are given in Sec. IV as the sum of contributions or interference entries from each of the unwanted uplinks and downlinks:

In particular, if the i th wanted link carries telephone channels in frequency division multiplex and if I_o is the interference objective, then the total interference noise at the output of the worst channel on link i (see Eq. (22)) must meet the condition

$$I_i = \sum_j (I_{ij})_{up} + \sum_j (I_{ij})_{down} \leq I_o \quad (75)$$

where each term in the sums has the form

$$I_{ij} = 10^9 (X_{ij}/C_i)/R_{ij} \quad (76)$$

and the sums are carried out over all interfering links ($j \neq i$).

Similarly, if the wanted link carries a television signal, and if ρ_o is the protection ratio for interference from a signal of the same kind, then the total unwanted-to-wanted signal ratio on link i (see Eq. (23)) must meet the condition

$$\left(\frac{X}{C}\right)_i = \sum_j (X_{ij}/C_i)_{up} + \sum_k (X_{ik}/C_i)_{down} \leq \rho_o^{-1} \quad (77)$$

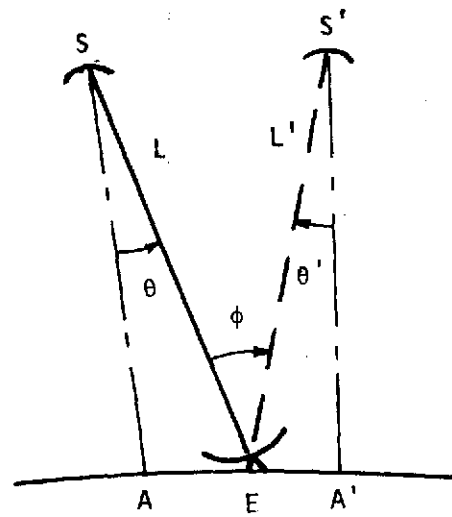
Here, the terms in the sums represent the effective unwanted-to-wanted signal ratio as a result of interference from the j th link and are given by

$$\left(\frac{X_{ij}}{C_i}\right) = \frac{1}{Q_{ij}} \frac{X_{ij}}{C_i} \quad (78)$$

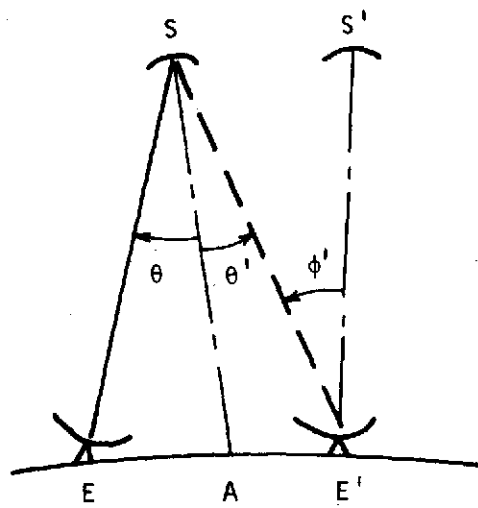
where Q_{ij} is the interference weighting factor defined in Eqs. (31) and (36).

Referring to conditions (1) or (3), it is seen that there is no unique way of satisfying the interference constraint; it is only required that the weighted sum of the X_{ij}/C_i over all interfering links be restricted. But the key to configuring systems so as to keep the sum of the interference contributions within bounds lies in understanding how to control the individual interference entries represented by Eqs. (76) and (78).

Expressing such an interference contribution in terms of the parameters of the wanted and unwanted links, it is possible to see how these parameters affect sharing and to judge the relative effectiveness of various sharing tactics--i.e., the individual design choices that enhance orbit-spectrum utilization. For this purpose, consider the downlink path geometry sketched in Fig. 22a. The wanted signal path from satellite S to earth station E is shown by the solid line and the unwanted signal path from the interfering satellite S' to E by a dashed line. These paths have losses L and L' and make angles



a. Downlink interference



b. Uplink interference

Fig. 22--Geometry and notation for wanted and unwanted paths

θ and θ' , respectively, with the satellite antenna axes SA and S' A'. The angle between the paths--the separation of the satellites viewed from the earth station--is denoted φ .

When the wanted downlink carries an FDM/FM signal, the single-entry interference contribution in dB relative to 1 pWOp, obtained from Eq. (76) by expressing X_{ij}/C_i in terms of the equipment and path parameters, is

$$10 \log I_{\text{down}} = \Delta E_S + \Delta g_S^+ + \Delta L - g_E^+(\varphi) + 90 - 10 \log R \quad (79)$$

where

$$\Delta E_S = 10 \log (E_{S'}/E_S) = \text{difference in satellite eirps (dB)}$$

$$\Delta g_S^+ = g_S^+(\theta) - g_{S'}^+(\theta') = \text{difference in satellite antenna angular discrimination (dB)}$$

$$\Delta L = 10 \log (L/L') = \text{difference in path losses (dB)}$$

$$10 \log R = \text{receiver transfer characteristic for interference from S' into E (dB)}$$

and, in general, $g_A^+(\alpha)$ is the co-polarized angular discrimination of antenna A at off-axis angle α as defined in Eq. (54). If the wanted and unwanted transmissions are cross-polarized, the interference contribution is given by the right side of Eq. (79) less the overall downlink polarization discrimination

$$10 \log \left[\delta_{S'}^{-1}(\theta') + \delta_E^{-1}(\varphi) + \sin^2 \epsilon \right]^{-1} \quad (80)$$

where ϵ is the angular misalignment of polarization axes and, in general, $\delta_A(\alpha)$ is the polarization discrimination of antenna A at off-axis angle α as defined in Eq. (43). Since the polarization discrimination of the individual antennas varies with off-axis angle over the range from 10 to 1000 the overall discrimination term is always positive.

The expression for an uplink interference contribution is quite similar to Eq. (79). Referring to the notation and path geometry illustrated in Fig. 22b, it is easily demonstrated that, when the wanted and unwanted transmissions are co-polarized, the interference noise is

$$10 \log I_{up} = \Delta E_E + \Delta g_S^+ + \Delta L - g_E^+(\varphi') + 90 - 10 \log R \quad (81)$$

where

$$\Delta E_E = 10 \log (E_E^-/E_E) = \text{earth-station eirp difference (dB)}$$

$$\Delta g_S^+ = g_S^+(\theta) - g_S^+(\theta') = \text{difference in satellite antenna angular discrimination (dB)}$$

$$\Delta L = 10 \log (L/L') = \text{path loss difference (dB)}$$

$$10 \log R = \text{receiver transfer characteristic for interference from } E^- \text{ into } S \text{ (dB)}$$

As in the case of the downlink interference contribution, if the wanted and unwanted uplink transmissions are cross-polarized, a term representing the overall uplink polarization discrimination

$$10 \log \left[\delta_S^{-1}(\theta') + \delta_E^{-1}(\varphi') + \sin^2 \epsilon \right]^{-1} \quad (82)$$

must be subtracted from the right-hand side of Eq. (81).

The first four terms in Eqs. (79) and (81) (or five terms for cross-polarized interference) represent the ratio in dB of unwanted-to-wanted signal power. For both downlinks and uplinks it is seen that this ratio is given by the angular discrimination of the earth antenna, appropriately adjusted for eirp and path loss differences, and for the effects of satellite antenna pointing and polarization discrimination.

Although the uplink and downlink expressions are quite similar in form, there are important differences in the meaning of corresponding

terms. In the downlink case, for example, Δg_S^+ represents the difference in angular discrimination toward the earth station of the antennas on different satellites, whereas, in the uplink case, Δg_S^+ is the difference in the discrimination of the same antenna towards two different earth stations. A practical consequence of this distinction is that the magnitude of uplink interference contributions for a given satellite spacing and combination of wanted and unwanted signals can exhibit a spread in values of about ± 3 dB whereas the downlink contributions exhibit a negligible spread. Another difference lies in the interpretation of the earth-station angular discrimination term. In the downlink expression, the antenna in question is the receiving antenna on the wanted link, whereas in the uplink expression, it is the transmitting antenna on the unwanted link.

Despite these differences, the uplink and downlink expressions are similar enough that a good understanding of sharing tactics can be based on a discussion of only the downlink expression. For this discussion, suppose that I_1 is the maximum allowable interference for the single downlink interference entry represented by Eq. (79). The condition for acceptable interference is then $I \leq I_1$. Using Eqs. (79) and (80), this inequality may be written for the general case of cross-polarization as a condition on the angular discrimination of the receiving earth-station antenna

$$g_E(\varphi) \geq 10 \log \rho_1 + \Delta E_S + \Delta g_S^+ + \Delta L \quad (83)$$

$$= 10 \log \left[\delta_S^{-1}(\theta) + \delta_E^{-1}(\varphi) + \sin^2 \epsilon \right]^{-1}$$

where ρ_1 is the protection ratio corresponding to the single-entry interference allowance I_1 , and is given by

$$\rho_1 = 10^9 / (RI_1) \quad (84)$$

If the wanted link carries a TV/FM signal, a similar analysis beginning with Eq. (78) leads to an equation identical to Eq. (83)

except for the definition of the effective single-entry protection ratio ρ_1 . In this case, of course, ρ_1 is the interference protection-ratio objective itself, adjusted only as needed to apply to the single entry in question.

Regardless of the nature of the wanted and unwanted signals, the minimum satellite spacing ϕ_m which meets the interference objective is given by the value of ϕ which makes the earth-station angular discrimination just equal to the expression on the right-hand side of Eq. (83). Note that spacing computed in this way for U.S. latitudes should be reduced by about 10 percent before comparison with satellite spacings measured from the center of the earth.

SHARING TACTICS

Sharing tactics may be categorized by the term in Eq. (83) whose value they control, and the relative effectiveness of a particular tactic can in most cases be measured by the impact it has on the minimum allowable spacing ϕ_m . Generally speaking, effective tactics are those that either decrease the right-hand side of Eq. (83), or increase its left-hand side, for a given ϕ . The effect of the former is to reduce the discrimination required of the earth-station antenna; for a given antenna, this means a reduction in ϕ_m . The effect of the latter type of tactic is to reduce the ϕ_m at which the required discrimination is achieved. It should be noted in passing that certain combinations of tactics can reduce the right side of Eq. (83) to zero or less, which means that the interfering links can operate with zero satellite separation--i.e., from the same satellite. The discussion of specific sharing tactics begins with those that reduce the first, or protection-ratio, term on the right side of Eq. (83).

Increased Interference Objectives

For an FDM/FM link, probably the most obvious way to reduce the protection ratio is simply to increase the total interference objective and hence all of the single-entry objectives. Although the CCIR specifies a 1000 pWOp limit for interference from other satellite systems (see Fig. 4), it is possible, particularly for domestic systems,

that system applicants and the appropriate regulatory agencies could agree on a higher value without affecting the 10,000 pWOp total noise objective.

For example, when there is no sharing with terrestrial systems, as in the U.S. table of allocations for the 11.7 to 12.7 GHz band, the interference limit could be doubled without changing the thermal-noise and intermodulation objectives by reassigning the 1000 pWOp CCIR allowance for terrestrial interference to satellite systems. Another possibility, applicable to single-carrier-per-transponder operation, would be to assign the 1500 pWOp allowance for intermodulation in the satellite output amplifier to satellite system interference. Beyond this, a part of the thermal-noise allotment could be reassigned, but this would require an increase in the products of transmitter eirp and receiver figure-of-merit on the up- and downlinks. If such increases were applied uniformly to all sharing systems however, there would be no effect on the wanted-to-unwanted signal ratios, and hence spacings could be reduced in accordance with the increase in the absolute value of the interference objective.

The magnitude of the reduction in satellite separation made possible by increasing the allowable interference can be inferred from an inspection of Eqs. (83) and (84). Thus, multiplying I_1 by a factor k reduces the associated protection ratio and hence divides the angular discrimination required of the earth-station antenna by the same factor. When it is recalled from Sec. IV that the assumed angular discrimination varies with the inverse square of off-axis angle for individual reception broadcasting and as the inverse 2.5 power for all other services, it is seen that the minimum satellite spacing will be divided by factors of $k^{0.5}$ and $k^{0.4}$, respectively. For example, if the interference objective is doubled, the minimum spacing can be reduced by 29 percent for individual reception broadcasting, or by 24 percent for community reception broadcasting and for the fixed-satellite service. If no other system parameters are changed, orbit-spectrum utilization (in channels per MHz of bandwidth and degree of orbital arc) will be multiplied by these same factors.

In the case of television links, reducing the protection ratio by allowing more interference in exchange for less noise is not likely

to be an effective tactic when the output picture-signal-to-noise objective is 49 dB or higher. The problem is that the protection-ratio objective was defined as the input carrier-to-interference ratio which produced barely visible interference to just such a "noise-free" picture. To decrease the protection ratio objective below this value would be to allow interference that would be more than barely visible, even if the signal-to-noise ratio were increased at the same time.

This tactic could have some value where the noise objective permitted a certain degree of picture degradation; the protection ratio might then be lowered in exchange for an increase in the signal-to-noise ratio which left the picture quality unchanged. Unfortunately, the subjective effects of noise and interference are different and there are insufficient data to establish the tradeoff between them.

Higher Modulation Indices

A second way to reduce the single-entry protection ratio ρ_1 in Eq. (83) is to use a higher modulation index for the wanted signal. With FDM/FM wanted signals, the effect is to increase the receiver transfer characteristic R to which ρ_1 is inversely proportional. Assuming wideband modulation, R is nearly proportional to the cube of the wanted signal modulation index for both FDM/FM and TV/FM interference as shown by Eqs. (24) and (29), respectively. With TV/FM wanted signals, the protection ratio is proportional to the inverse square of modulation index as shown by Eqs. (33) and (37).

Increasing the modulation index can thus allow quite significant reductions in satellite spacing. For links carrying only FDM/FM signals, a k -fold increase in modulation index would permit satellite spacings to be divided by a factor of nearly $k^{1.2}$. Spacings for satellites carrying television, on the other hand, could be divided by a factor of $k^{0.8}$ for community reception and k for individual reception. For example, doubling the modulation index would permit a 43 percent spacing reduction for broadcasting satellites intended for community reception or for fixed satellites whose links carried television as well as telephone circuits.

Unfortunately, the decrease in spacing achieved by increasing modulation index does not translate into a corresponding increase in orbit-spectrum utilization. The reason is plain from Eqs. (6) and (15) which show that the rf bandwidth requirement increases linearly with modulation index. Thus, while there can be more satellites in a given orbital arc, the number of channels per satellite will be divided by a factor which is roughly equal to the fractional increase in modulation index. The net result is that orbit-spectrum utilization is not strongly affected by modulation index. To a first approximation it can be expected to be multiplied by $k^{0.2}$ for satellites carrying only FDM/FM, be divided by $k^{0.2}$ for community reception broadcasting satellites, and be unchanged for individual reception broadcasting.*

Offset Carrier Frequencies

A third way of reducing the required protection ratio for interference to both FDM/FM and TV/FM signals is to offset the carrier frequency of the interfering signal from that of the wanted signal. Reference to Figs. 8 and 9 for wanted FDM/FM signals and to Figs. 10 and 11 for wanted TV/FM signals shows that the protection ratio decreases relative to its value for co-channel operation as the frequency offset increases--the rate of decrease being dependent on the modulation indices of the wanted and unwanted signals. For offsets of half the rf bandwidth of the wanted signal, the tactic is called frequency interleaving and the result is a 10 to 15 dB reduction in the protection ratio for FDM/FM signals and a 5 to 10 dB reduction for TV/FM signals. With a sidelobe envelope decay exponent of 2.5, the spacing reductions corresponding to 5, 10, and 15 dB are, respectively, 37, 60, and 75 percent relative to the spacings for strictly co-channel operation. The corresponding increases in orbit-spectrum utilization are 58, 150, and 298 percent.

*The factors cited assume that rf bandwidth is directly proportional to modulation index, and so underestimate the improvement in orbit-spectrum utilization. With FDM/FM signals for example, increasing the rms modulation index from 1 to 2 should improve orbit-spectrum utilization by about 31 percent, while an increase from 2 to 4 yields a 24 percent improvement. The factor $k^{0.2}$ corresponds to a 15 percent improvement.

Such spacing reductions could be achieved, for example, by arranging satellites in orbit so that in each adjacent pair, the rf channels occupied by the carriers of one are displaced by half a channel bandwidth from those of the other. In practice, the technique is more commonly used in conjunction with the tactic of polarization discrimination (to be discussed below) in such a way that this degree of carrier overlap can exist in the same satellite, thus doubling the satellite channel capacity.

Eirp Difference Matched to Other System Differences

The second term in Eq. (83) represents the amount in dB by which the eirp of the "unwanted" satellite exceeds that of the wanted satellite. When the unwanted satellite has the lower eirp, the term is negative and serves to reduce the angular discrimination required of the wanted earth-station antenna. Thus the unwanted satellite can be located closer to the wanted satellite than it could be if it had the same eirp.

On the other hand, when considering interference to the link supported by the satellite with the lower eirp, the eirp difference has just the opposite effect. It increases the required angular discrimination and hence the spacing required to protect the link compared with that for equal eirp. To protect both links, the larger of the calculated separations must be used. If the two earth-station antennas are of about equal size and the signals on the links require about the same protection ratios, it is obvious that the spacing that protects both will be smallest when the satellites have the same eirp.

Equal eirps are by no means appropriate in the more general case where there are differences in earth-station antenna sizes or in the protection-ratio requirements of the two interfering links. Consider the case of dissimilar but co-polarized satellites, B and F, adjacent to one another in orbit and having eirps E_B and E_F , respectively. Ignoring the terms in Δg_S and ΔL , it is readily shown from Eq. (83) that the separations required to protect each satellite from the other will be equal when the ratio of eirps is adjusted so that

$$\frac{E_B}{E_F} = \frac{D_F}{D_B} \frac{\rho_{BF}}{\rho_{FB}} \quad (85)$$

where D_B and D_F are the earth-station antenna diameters and ρ_{BF} and ρ_{FB} are the protection ratios for the links from satellites B and F, respectively.

For example, assuming the same protection-ratio requirements, a broadcasting satellite using 3 ft receiving antennas should have a 10.3 dB eirp advantage over a fixed satellite working into 32 ft earth stations in order that the satellite separations to protect one system from the other will be the same for both.

Crossed-Path Geometry

The third term in Eq. (83) is the amount Δg_S by which the angular discrimination of the wanted satellite transmitting antenna in the direction of the receiving earth station exceeds that of the unwanted satellite. When all satellite antennas are aimed at the same point, as is normally the case for domestic fixed-satellite systems serving the entire country, the off-axis angles θ and θ' in Fig. 22 are nearly equal and, assuming identical satellite antenna patterns, the term is negligibly small.

On the other hand, when satellites are aimed at different points, as in the case of broadcasting satellites with different service areas, θ' will exceed θ and the term Δg_S will be negative throughout each service area. The magnitude of Δg_S at the center of the wanted service area and the values to which it increases at the service-area boundaries depend, of course, on the relative values of θ and θ' . These in turn depend on the dimensions of the wanted service area relative to the distances separating it from the service areas of adjacent unwanted satellites.

By choosing satellite positions so that longitudinally adjacent service areas are not served by adjacent satellites, it is possible to make θ' larger, and hence Δg_S more negative, for precisely those unwanted satellites whose separation ϕ from the wanted satellite are smallest. By thus decreasing the angular discrimination required of

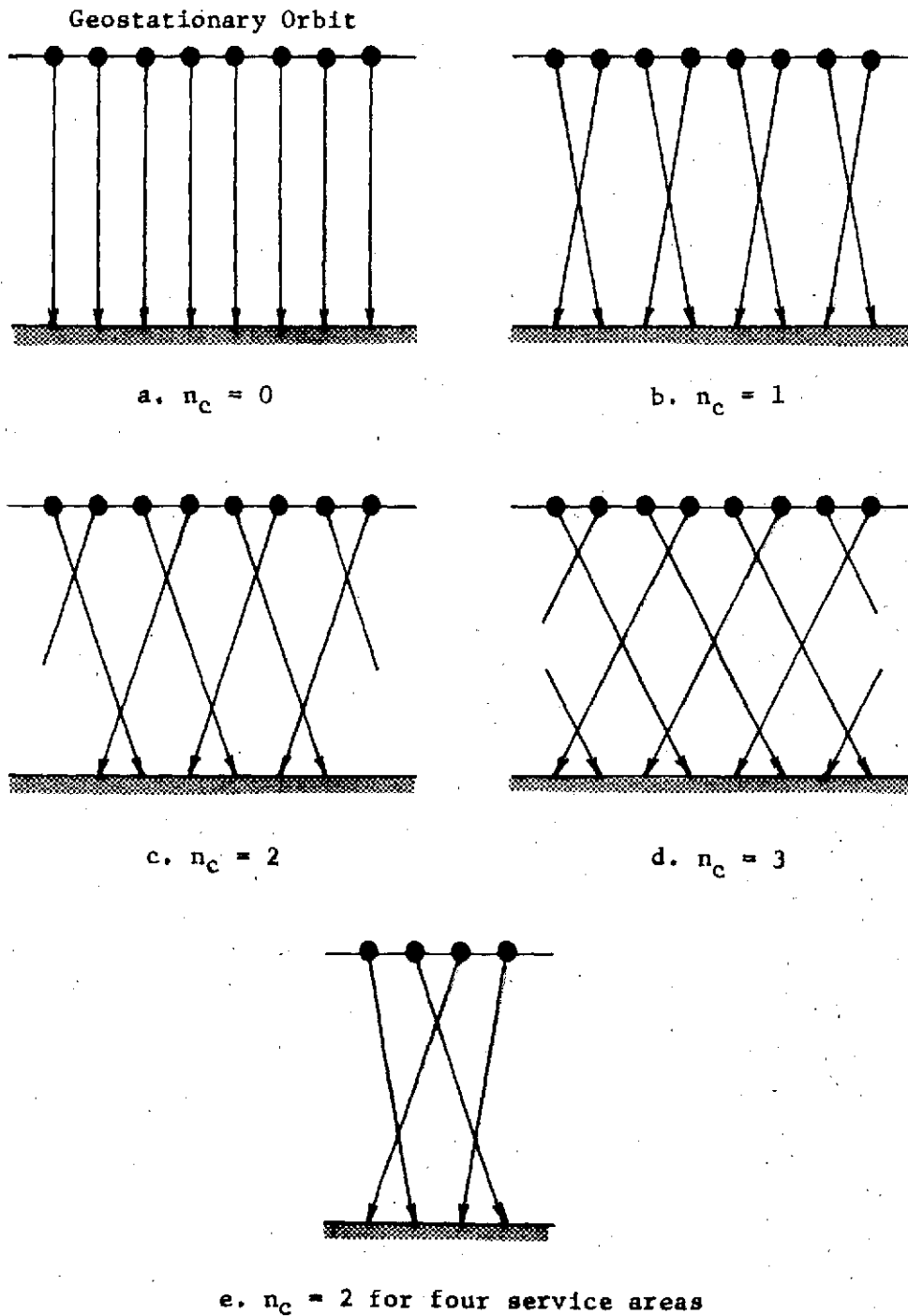


Fig. 23--Schematic examples of crossed-path geometry

the ground receiving antennas, the spacing between adjacent satellites can be decreased relative to that which would be required if satellite positions were assigned sequentially in accordance with the longitude of their service areas.

Arranging satellites in the manner described will be referred to as "crossed-path geometry," since the wanted signal paths of necessity must intersect one another. The tactic was first described by Matsushita,⁽⁵¹⁾ and schematic illustrations are given in Fig. 23 for the case where both service areas and satellites are equally spaced at the same longitudinal interval. The different arrangements can be identified by the number of crossings n_c involved when there are a large number of service areas as in Figs. 23a-d. An adaptation of twice-crossed geometry ($n_c = 2$) for a system of four service areas is shown in Fig. 23e.

The reduction in spacing afforded by crossed-path geometry relative to the noncrossed case ($n_c = 0$) depends on the value of n_c , the antenna patterns assumed, the longitudinal separation of the service areas, and the required protection ratio; it is apparent that the once-crossed case ($n_c = 1$) yields little or no reduction.

In the twice-crossed case however, crossed-path operation can increase the wanted-to-unwanted signal ratio for a given satellite spacing by several dB relative to that for the noncrossed case. For example, assuming the configuration shown in Fig. 23c, with a satellite antenna beamwidth of 4 deg and a ground receiving antenna having a beamwidth of 2.5 deg and a CCIR community-reception sidelobe envelope (see Fig. 17), Matsushita⁽⁵¹⁾ reported an increase ranging from 0 dB at a satellite separation of 5.5 deg to a maximum of about 6 dB at a 13 deg separation. For a protection ratio of 30 dB, the spacing could be reduced from 17 deg to 12 deg, a 29 percent reduction.

To test the crossed-path tactic for domestic applications, the computer program described in the Appendix was used to determine the dependence of wanted-to-unwanted signal ratio C/X on satellite spacing for the cases $n_c = 0$ and $n_c = 2$. In this test, the baseline broadcasting-satellite systems for individual reception (see Table 8) were assumed to provide service to the four U.S. time zones (see Table 10).

The results showed that, compared with the noncrossed reference geometry, crossed-beam operation had the following effects: At the centers of the service areas, it reduced the value of C/X by amounts ranging from 2 to 9 dB for all time zones at the widest spacing tested (10 deg), but increased C/X by about 2 dB for two of the time zones at the narrowest spacing (4 deg). On the other hand, at the interface between service areas, crossed-beam operation increased C/X by at least 5 dB for all time zones and at all spacings.

Considering only the worst values of C/X , the variation with spacing at the center and edges of the service areas are displayed for $n_c = 0$ and $n_c = 2$ in Fig. 24. From these curves, it may be concluded that, for the case tested, crossed-beam operation has only a small effect (± 2 dB) on interference vulnerability at the centers of service areas but, by reducing the overall variation of C/X within a service area, it provides a significant (5 to 6 dB) improvement at the service area boundaries. For a protection ratio of 30 dB at the edge of the service areas, satellite spacing can be reduced from about 11.8 to 7.7 deg, a 35 percent reduction.

Cross-Polarized Antennas

The path-loss-difference term, ΔL , in Eq. (83) will not be considered. Its numerical value is normally less than 1 dB, and in no case does it appear to provide the basis for a sharing tactic.

The remaining term on the right side of Eq. (83) measures the overall polarization discrimination of the downlink antennas when operated with crossed polarizations. If the wanted and unwanted signals emanate from the same satellite ($\varphi = 0$ in Fig. 22), and the earth station is within the main lobe of this satellite ($\theta' = \theta < \theta_0/2 =$ half the satellite half-power beamwidth), an overall polarization discrimination of from 20 to 25 dB is easily achieved. When the unwanted satellite lies outside the main lobe of the earth-station antenna ($\varphi > \varphi_0/2$), the overall discrimination may be reduced to between 6 and 10 dB.

If the single-entry protection ratio is less than the available net on-axis polarization discrimination of 20 to 25 dB, use of the

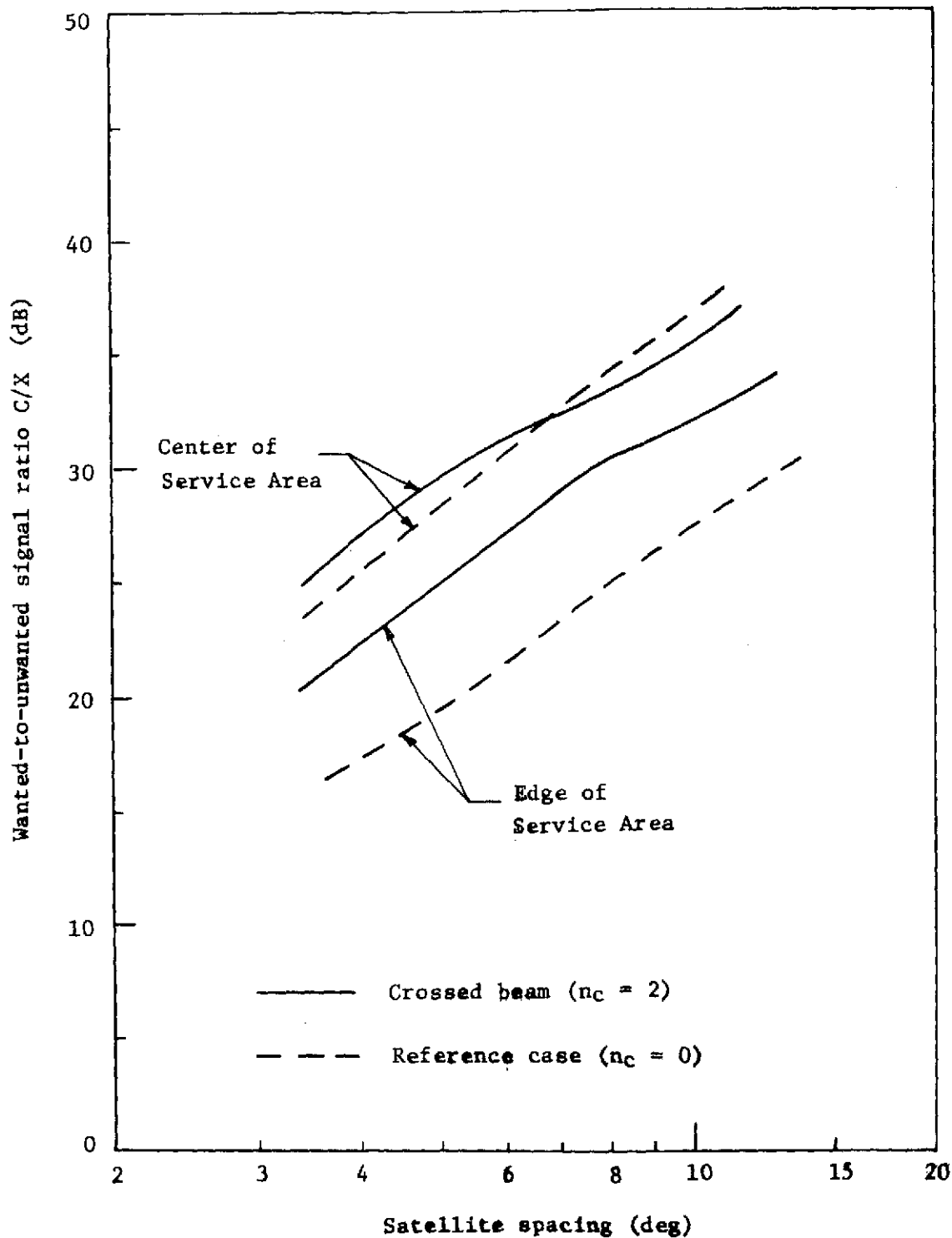


Fig. 24--Worst-case values of wanted-to-unwanted signal ratios for crossed-beam deployment of broadcasting satellites

cross-polarized tactic makes it possible to radiate two co-channel signals from the same satellite. In practice however, the prerequisite condition is not usually met unless very wideband (high modulation index) signals are involved.

In addition, the 6 to 10 dB of polarization discrimination available in the sidelobe region of an earth-station antenna can be used to achieve a reduction in the spacing between adjacent interfering satellites carrying co-channel signals by factors of 1.74 to 2.51, respectively, assuming a sidelobe envelope decay exponent of 2.5. For example, using co-channel, horizontally co-polarized operation, described schematically in Fig. 25a, as a reference, cross-polarized operation with a sidelobe polarization discrimination of 7.5 dB permits satellite spacings to be cut exactly in half as shown schematically in Fig. 25b.

As noted earlier, cross-polarization is often combined with the tactic of frequency interleaving. When the interfering signals are both cross-polarized and interleaved in frequency, radiation from a single satellite becomes feasible even at normal modulation indices, since the interleaving reduces the protection ratio to a value small enough to be canceled by 20 to 25 dB of on-axis polarization discrimination. This combined use of tactics is illustrated in Fig. 25c and leads to the previously mentioned doubling of satellite capacity, with no effect on satellite spacing.

Alternatively, if frequency interleaving and cross-polarization are used on adjacent satellites, the combination of a 5 to 15 dB reduction in protection ratio and the 6 to 10 dB of sidelobe polarization discrimination can divide spacings by factors of from 2.1 (for 11 dB) to 7.6 (for 25 dB) compared with co-channel co-polarized operation. This possibility is shown in Fig. 25d, where it is seen that each signal is subject to four, rather than two, interference entries from adjacent satellites.

Finally, if the combination of frequency interleaving and cross-polarization is used on both the same satellite and on adjacent satellites, satellite capacity can be doubled and spacings usually cut in half as sketched in Fig. 25e. It will be noted that in this case,

		Satellite Position					
		1		2		3	
Channel Number	1	H		H		H	
	2	H		H		H	

a. Reference Co-polarized, Co-channel operation

		1	1a	2	2a	3
Channel Number	1	H	V	H	V	H
	2	H	V	H	V	H

b. Cross-polarized, co-channel operation on adjacent satellites at half spacing

		1		2		3
Channel Number	1	H		H		H
	1a	V		V		V
	2	H		H		H
	2a	V		V		V

c. Cross-polarized, frequency-interleaved operation on same satellites with no change in spacing

		1	1a	2	2a	3	3a
Channel Number	1	H	V	H	V	H	V
	1a	V	H	V	H	V	H
	2	H	V	H	V	H	V
	2a	V	H	V	H	V	H

d. Cross-polarized, frequency-interleaved operation on adjacent satellites at fractional spacing

		1	1a	2	2a	3
Channel Number	1	H	V	H	V	H
	1a	V	H	V	H	V
	2	H	V	H	V	H
	2a	V	H	V	H	V

e. Cross-polarized, frequency-interleaved operation on both the same and on adjacent satellites at half spacing

Fig. 25--Alternative uses of crossed polarization and frequency interleaving

most signals are subject to eight interference entries, considering only signals on the same and the two immediately adjacent satellites. Hence the sum of the amount by which the protection ratio is reduced and the magnitude of the overall polarization discrimination must be at least 14 dB.

The implications for orbit-spectrum utilization of using polarization discrimination either by itself or in combination with frequency interleaving are straightforward. Again using co-polarized co-channel operation as a reference case (Fig. 25a), the utilization is doubled by the tactics shown in Figs. 25b and 25c, and quadrupled by their use as illustrated in Fig. 25e. The increase in utilization represented by the arrangement of Fig. 25d will be comparable to that of Fig. 25e for the same combination of signal characteristics and antenna performance.

Earth-Station Angular Discrimination

Turning to the left side of Eq. (83), the question is, How can the earth-station receiving antenna be designed to achieve the discrimination requirement represented by the right side of the equation at smaller off-axis angles ϕ ? The obvious answer, of course, is by making it larger, but this "tactic" for increasing orbit-spectrum utilization can have both economic and operational penalties. However, even with the largest antenna aperture that can be used without an undue impact on total system cost, orbit-spectrum utilization can still be improved over that possible with conventional antennas by using comparatively simple techniques of sidelobe reduction.⁽⁵²⁾ It is necessary however that these techniques reduce sidelobe levels to the point where the angular discrimination close to the main lobe exceeds the single-entry protection ratio.

The potential increase in orbit-spectrum utilization under these conditions can be inferred from the reference satellite-antenna pattern labeled B-C in Fig. 18. This pattern is intended to represent the nominal 40 dB limit assumed for current sidelobe-reduction techniques, but reductions less than this would also be very useful when applied to earth-station antennas. For example, if the discrimination requirement given by the right side of Eq. (83) is 30 dB, pattern B-C

shows that satellite spacing can be reduced from the value of $6 \varphi_0$ required with conventional antenna performance (represented by pattern B-A in Fig. 18) to $1.2 \varphi_0$, where φ_0 is the half-power beamwidth of the antenna. This reduction translates directly into a fivefold increase in orbit-spectrum utilization.

DETERMINATION OF COMPATIBLE ORBITAL SPACINGS

In the foregoing discussion of sharing tactics, considerable attention was given to the orbital separation that must be maintained between two satellites to keep the interference from a link of one satellite into a link of the other below a prescribed level (the single-entry interference objective). The more general question, to be addressed now, is how to deploy the satellites of a number of different systems so that, for each link in each satellite system, the sum of the single-channel entries--that is, the total interference--meets the overall interference objective for the link.

It is not sufficient to have a computer simulation program that will determine the levels to be expected in a prescribed configuration of systems. Such a program is indispensable for verifying the interference compatibility of a configuration once arrived at and, used iteratively, it can be a powerful tool in converging on still more efficient configurations. The more basic need, however, is for approximate methods that will lead to orbital configurations worthy of more detailed examination.

The multiple-system problem is straightforward and permits an approximate solution in closed form for only one simple but very important reference case. This is the "homogeneous" configuration in which identical satellites, all carrying the same type of signal and serving identical earth stations, are equally spaced across the entire visible arc of the geostationary orbit. Each satellite has a coverage or service area determined by the beamwidth and pointing direction of its transmitting antenna. These service areas are all of the same size, since it was assumed that the satellites are identical, but it is important to distinguish between the case where the service areas are coincident (all satellite antennas aimed at the same point on earth),

from that where they do not overlap. The geometry of the two cases is sketched in Figs. 26a and 26b, respectively; the latter with the assumption that the boundaries of adjacent service areas, as defined by the 3 dB angular-discrimination contour of the satellite antennas, are tangent. These two cases will be considered in turn.

Homogeneous Systems with Coincident Service Areas

To analyze the overlapping-coverage case let φ_h be the satellite spacing in longitude--i.e., the angular separation measured at the center of the earth--and let $2N$ be the total number of satellites visible above the horizon. If path loss differences are neglected, the downlink unwanted-to-wanted signal ratio resulting from the satellite at separation $k\varphi_h$ from the wanted satellite is simply

$$\frac{X_k}{G} = \frac{G(k\varphi_h)}{G_o} \quad (86)$$

where

$G(\varphi)$ = earth-station antenna gain at off-axis angle φ

$G_o = G(0)$ = on-axis gain of earth-station antenna

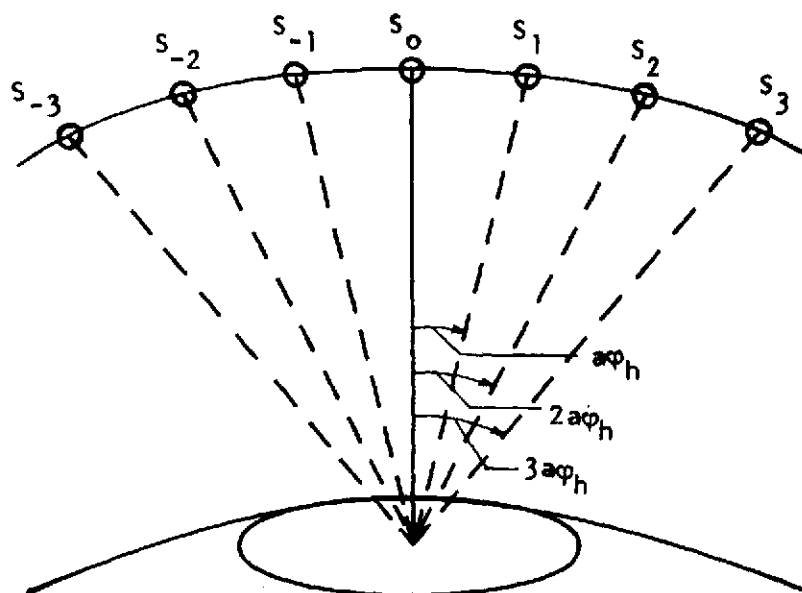
a = ratio of topocentric (measured at surface of earth)
satellite spacing to geocentric spacing

The ratio $G(\varphi)/G_o$ is given by the sidelobe angular discrimination pattern envelope appropriate to the service in question as described in Eqs. (59), (55), and (56), which may be written

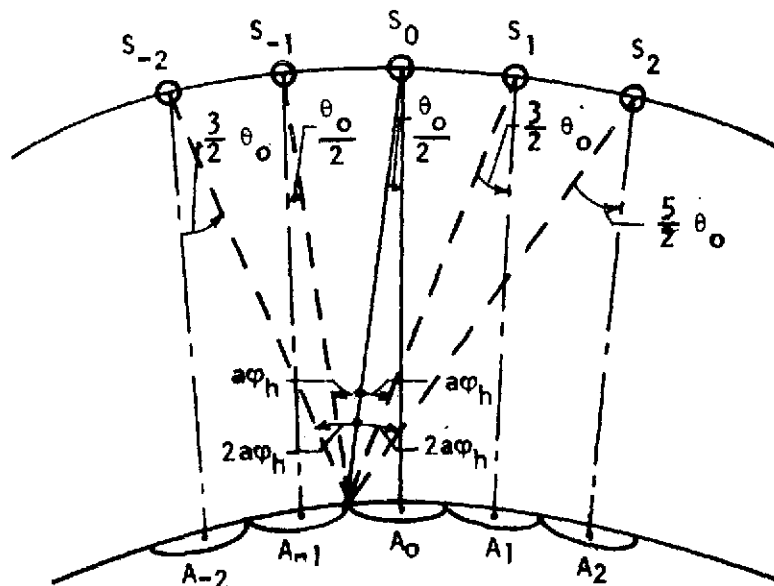
$$\frac{G_o}{G(\varphi)} = \begin{cases} 14.13 \varphi_o^{0.5} (\varphi/\varphi_o)^{2.5}, & (F = \text{fixed satellite}) \\ 11.22 (\varphi/\varphi_o)^{2.5}, & (B = \text{broadcasting-satellite community reception}) \\ 7.94 (\varphi/\varphi_o)^2, & (I = \text{broadcasting-satellite individual reception}) \end{cases} \quad (87)$$

(B = broadcasting-satellite community reception)

(I = broadcasting-satellite individual reception)



a. Homogeneous satellite systems with overlapping coverage



b. Homogeneous satellite systems with nonoverlapping coverage

Note: Wanted signal paths shown by solid line; unwanted signal paths by dashed line

Fig. 26--Geometry with ring of homogeneous satellites

where φ_0 is the half-power beamwidth of the earth-station antenna in degrees, and the formulas apply with the restrictions on φ and φ_0 given in Sec. IV. If these restrictions are ignored, and if it is assumed that the angle ratio a is independent of the satellite index k (implying that satellite spacings are equal when viewed from the earth station), the total downlink unwanted-to-wanted signal ratio becomes

$$\frac{X}{C} = \sum_{k=-N}^N \frac{X_k}{C} = 2 \sum_{k=1}^N \frac{G(k a \varphi_h)}{G_o} \quad (90)$$

$$= \begin{cases} \frac{(a \varphi_h / \varphi_0)^{-2.5}}{7.06 \varphi_0^{0.5}} \sum_{k=1}^N k^{-2.5}, & (F) \end{cases} \quad (91)$$

$$= \begin{cases} \frac{(a \varphi_h / \varphi_0)^{-2.5}}{5.61} \sum_{k=1}^N k^{-2.5}, & (C) \end{cases} \quad (92)$$

$$= \begin{cases} \frac{(a \varphi_h / \varphi_0)^{-2}}{3.97} \sum_{k=1}^N k^{-2}, & (I) \end{cases} \quad (93)$$

Finally, if it is assumed that the number of visible satellites is large, then the finite sums, which represent the ratio of total interference to that produced by the two nearest satellites, can be approximated by the infinite sums

$$\sum_{k=1}^{\infty} k^{-2.5} = \zeta(2.5) = 1.341$$

$$\sum_{k=1}^{\infty} k^{-2} = \zeta(2) = 1.645$$

Where ζ is the Riemann zeta function. Thus, the homogeneous satellite spacings which make the wanted-to-unwanted signal ratio just equal to the downlink protection ratio ρ_{down} are given by*

$$\varphi_h = \begin{cases} 0.468 \varphi_o^{0.8} \rho_{\text{down}}^{0.4}, & \text{(F)} \\ 0.513 \varphi_o \rho_{\text{down}}^{0.4}, & \text{(C)} \\ 0.585 \varphi_o \rho_{\text{down}}^{0.5}, & \text{(I)} \end{cases} \quad \begin{matrix} (94) \\ (95) \\ (96) \end{matrix}$$

where the angle ratio a has been taken as 1.1, a value appropriate to the midlatitude of the United States.

It is also useful to have expressions for the homogeneous satellite spacing directly in terms of such system parameters as the earth-station antenna diameter D and the modulation index m (or M) of the rf signal. For this purpose, Eq. (52) may be used to express φ_o in terms of D . With an antenna efficiency of 55 percent and a carrier frequency of 11.7 GHz, for example, the half-power beamwidth is

$$\varphi_o = 5.45/D \quad (97)$$

where φ_o is in degrees and D is in feet.

To express the downlink protection ratio in terms of the rms modulation index m of the FDM/FM signal carried by a homogeneous fixed-satellite system, let I_o be the total clear-weather interference objective in pWOp, and let r_F represent the factor by which the total interference exceeds that on a typical downlink. Then, from the definition of the receiver transfer characteristic, the downlink protection ratio is given by

$$\rho_{\text{down}} = 10^9 r_F / (I_o R) \quad (98)$$

* It should be noted that Eq. (96) will become inapplicable as ρ_{down} approaches 1000 (30 dB) because Eq. (89) doesn't apply for values of φ which cause $G_o/G(\varphi)$ to exceed this value.

where I_o is expressed in pWOp and $R = R_{FF}(m, m, 0)$ is the receiver transfer characteristic for co-channel interference between a pair of the assumed n -channel EDM/FM signals. Using the approximation given by Eq. (28),

$$R = 1.78 f(n)(1 + 9.5 m^3) \quad (99)$$

where $f(n)$ was defined in Eq. (25). Combining Eqs. (94), (97), (98), and (99), the minimum spacing in degrees for a ring of homogeneous fixed satellites is

$$\varphi_h = \frac{5746 r_F^{0.4}}{[f(n)I_o(1 + 9.5 m^3)]^{0.4} n^{0.8}}, \quad (F) \quad (100)$$

The corresponding expression for the broadcasting-satellite service may be obtained with the aid of Eq. (33) for the protection ratio for interference between two identical television signals. Thus, if M is the peak modulation index, the total effective wanted-to-unwanted signal ratio must not drop below

$$\rho_o = 891/M^2 \quad (101)$$

Substitution from Eqs. (97) and (101) into Eqs. (95) and (96) yields*

$$\varphi_h = \begin{cases} \frac{42.3 r_C^{0.4}}{DM^{0.8}}, & (C) \quad (102) \\ \frac{95.2 r_I^{0.5}}{DM}, & (I) \quad (103) \end{cases}$$

where r_C and r_I are, respectively, the ratios of downlink protection ratio to total protection ratio for community and individual reception.

If the picture signal-to-weighted noise ratio objective $(S_p/N_w)_o$

*The footnote on the preceding page also applies to Eq. (103).

is less than 49 dB, the interference-masking effect of thermal noise may be taken into account as discussed in connection with Eq. (32) by multiplying the protection ratio in Eq. (101) by the factor

$$q = 10^{-[49 - 10 \log (S_p/N_w)_o]/10} \quad (104)$$

In view of Eqs. (95) and (96), the effect of masking by noise is to multiply the homogeneous spacing angle for community reception by $q^{0.4}$ and that for individual reception by $q^{0.5}$. For example, with the baseline thermal-noise objective of 43 dB assumed for individual reception, $q = 0.25$, and the spacing of the corresponding broadcasting satellites could be reduced by half.

Homogeneous Systems with Non-Overlapping Service Areas

The foregoing equations for homogeneous satellite spacings were derived on the assumption that the same incident power flux density is received from all interfering satellites. This may be a valid assumption for domestic fixed-satellite systems whose antenna footprints cover the entire country. It will not be true for broadcasting satellites that use spot beams to cover non-overlapping service areas. As noted in Sec. II, the first broadcasting satellites are likely to be of this type to permit the use of simple receiving installations with non-steerable antennas.

In calculating satellite spacings for a homogeneous ring of satellites with non-overlapping service areas, the directivity of the satellites antennas must be taken into account because the antennas are not all aimed at the same point. For a broadcasting-satellite antenna with no sidelobe control, the directivity envelope suggested by the CCIR is given by Eq. (62), which is equivalent to Eq. (88). At the center of a service area, this leads to a 10.5 dB reduction in the unwanted signal power from the closest satellites (S_{-1} and S_1 in Fig. 26) when compared with the case of coincident service areas.

With non-overlapping service areas however, the worst interference occurs at the boundary between areas, however, the worst interference Referring to the path geometry shown in Fig. 26b, the unwanted-to-wanted

signal ratio at the service area boundary for satellite S_0 is determined almost entirely by the contributions from satellites S_{-1} and S_1 , and so may be written

$$\frac{X}{C} = \frac{G(a\varphi_h)}{G_o} \left[1 + \frac{G_S(3\theta_o/2)}{G_S(\theta_o/2)} \right] \quad (105)$$

where $G_S(\theta)$ is the gain of the satellite antenna at off-axis angle θ . Using Eq. (88) for G_S , and setting C/X equal to the required downlink protection ratio, the homogeneous spacings for the ground receiving antenna envelopes previously considered for satellite broadcasting are*

$$\varphi_h = \begin{cases} 0.354 \varphi_o \rho_{\text{down}}^{0.4}, & \text{(C)} \\ 0.333 \varphi_o \rho_{\text{down}}^{0.5}, & \text{(I)} \end{cases} \quad (106) \quad (107)$$

These spacings are seen to be, respectively, 31 percent and 43 percent less than those given by Eqs. (95) and (96) for the case of coincident service areas.

Proceeding as before, the equations for φ_h may also be expressed directly in terms of the ground receiving-antenna diameter and the TV modulation index.*

$$\varphi_h = \begin{cases} \frac{29.2 r_c^{0.4}}{DM^{0.8}}, & \text{(C)} \\ \frac{54.3 r_I^{0.5}}{DM}, & \text{(I)} \end{cases} \quad (108) \quad (109)$$

Again, the interference-masking effects of thermal noise may be acknowledged by multiplying the spacings given by Eqs. (108) and (109) by $q^{0.4}$ and $q^{0.5}$, respectively, where q is given by Eq. (104). Since q is by definition less than unity, the effect is to reduce the spacing.

Spacings for Homogeneous Baseline Systems

The spacing for a homogeneous configuration of satellite systems is of considerable interest because it represents the minimum spacing

* Eqs. (107) and (109) will not apply for large values of ρ_{down} or small values of M for the reasons cited in connection with Eqs. (96) and (103).

possible for systems having the specified combination of antenna diameter and modulation index. It is the spacing that would yield the highest utilization of the orbit-spectrum resource if allocated exclusively to such systems. The homogeneous spacing is also of importance in devising deployments of dissimilar satellite systems, because the orbit-spectrum resource can be assigned in such a way that similar systems occupy contiguous portions of the resource (adjacent orbital positions and rf channels). Such "local homogeneity" allows the permitted satellite spacing to approach their homogeneous values within each such portion of the resource.

It will be noted that the homogeneous system spacing does not depend directly on such system parameters as eirp, thermal-noise objectives, receiving-system noise temperature, and fading margins; these parameters enter the problem only to the extent that they influence the choice of values for the independent variables of earth-station antenna diameter and modulation index. The other parameter on which the homogeneous spacing depends is the ratio of the downlink wanted-to-unwanted signal ratio to the total or effective wanted-to-unwanted signal ratio (denoted r_F , r_C , or r_I in the equations for spacing). This parameter depends in turn on the expected ratio of downlink-to-uplink interference and may be estimated from a comparison of Eq. (79) with Eq. (80).

For homogeneous systems, the comparison suggests that on a typical fixed-satellite link, the downlink interference contribution I_{down} will exceed the uplink contribution I_{up} by the same amount that the earth-station angular discrimination on the uplink exceeds that on the downlink. Since the earth-station antennas will normally be of the same diameter, it follows that the ratio of interference contributions will equal the square of the ratio f_{up}/f_{down} of uplink to downlink carrier frequencies

$$I_{down} = (14/11.7)^2 I_{up} = 1.43 I_{up}$$

whence

$$r_F = (I_{up} + I_{down})/I_{down} = 2.43/1.43 = 1.70 \quad (110)$$

For broadcasting-satellite systems serving non-overlapping service areas, the difference in dB between the uplink and downlink wanted-to-unwanted signal ratios at the boundary between service areas will also be equal to the difference in the discrimination of the uplink and downlink earth-station antennas. In general though, these antennas will have different diameters D_{up} and D_{down} , so the ratio of C/X_{up} to C/X_{down} will be given by

$$s = (f_{up} D_{up})^2 / (f_{down} D_{down})^2 \quad (111)$$

and the desired ratio of downlink-to-total C/X by

$$r = (s + 1)/s \quad (112)$$

In the case of community reception, baseline antenna diameters of 16 and 12 ft were assumed for the uplink and downlink, respectively, so that, on the average, the uplink C/X will exceed that of the downlink by a factor of 2.55 (4 dB). This implies that the downlink protection ratio should exceed the total protection ratio by a factor

$$r_C = 1.393, (1.4 \text{ dB}) \quad (113)$$

By similar reasoning, the ratio of downlink-to-total protection ratio for the baseline antenna diameters of 16 and 3 ft assumed for individual reception is very nearly unity.

$$r_I = 1.025, (0.1 \text{ dB}) \quad (114)$$

Using the baseline values of r_F , r_C , and r_I in Eqs. (100), (108), and (109), respectively, the dependence of homogeneous satellite spacing on antenna diameter was calculated for various modulation indices appropriate to the baseline fixed-satellite and broadcasting-satellite systems described in Sec. III. The results are shown in Fig. 27 and correspond to a total interference noise objective of 1000 pWOp for the fixed-satellite systems, and no interference-masking ($q = 1$) for the broadcasting-satellite systems.

The modulation indices illustrated for the fixed-satellite systems

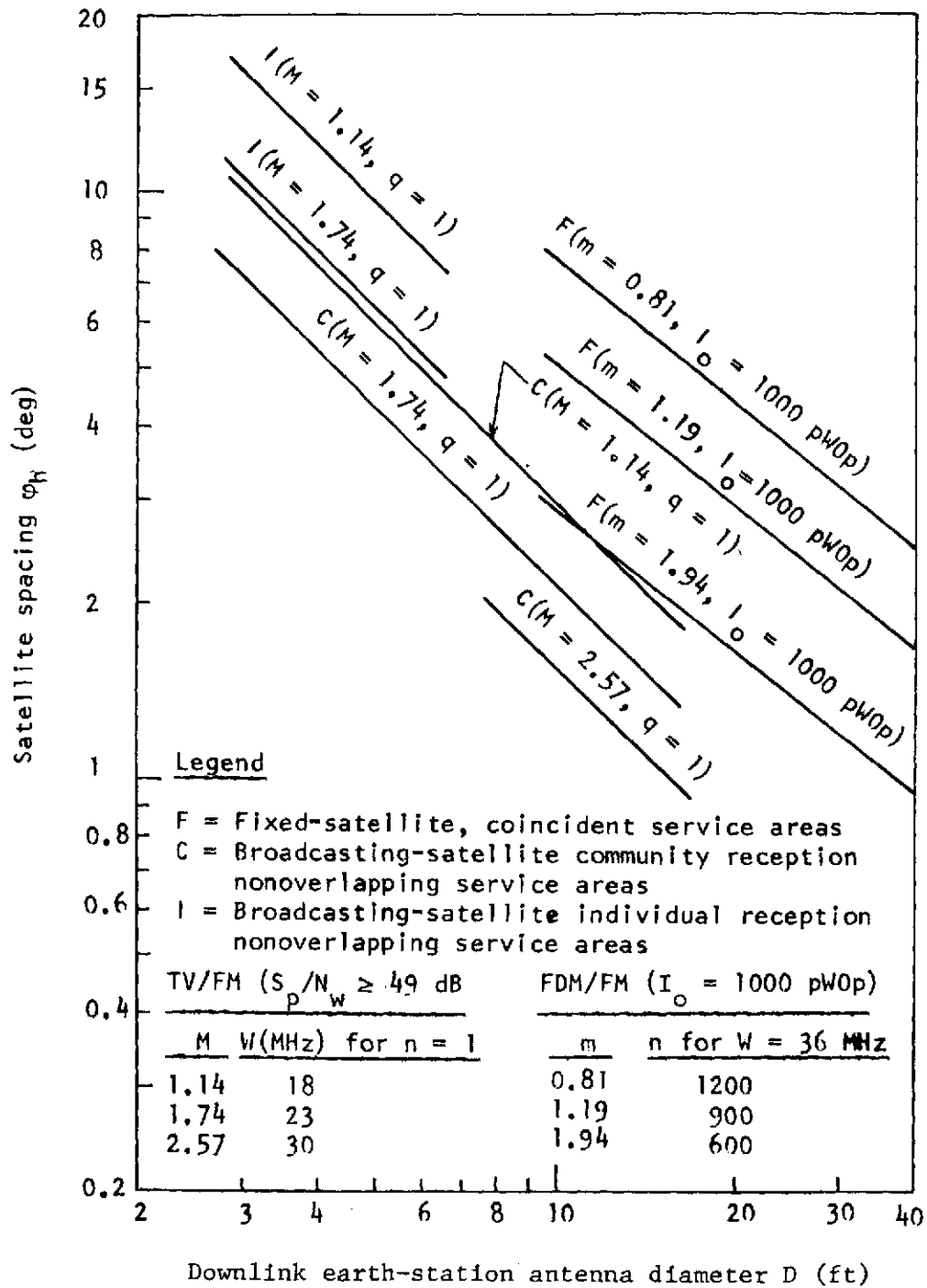


Fig. 27--Satellite spacings for homogeneous systems with co-channel, co-polarized signals

correspond to operation in a 36 MHz rf bandwidth with 1200 channels ($m = 0.81$), 900 channels ($m = 1.19$), and 600 channels ($m = 1.94$). The 1200 channel FDM/FM carrier represents nearly the maximum bandwidth-limited capacity of the baseline fixed-channel transponder when operating into the baseline 32 ft earth station. A 900 channel carrier in 36 MHz represents the maximum capacity for power-limited operation with the baseline thermal-noise and threshold margin objectives but does not require the full transponder output power. Use of 36 MHz of bandwidth for the transmission of 600 channels requires the same power as for 900 channels (to meet the assumed margin requirement), but yields a 6 dB higher output signal-to-noise ratio and permits closer satellite spacings.

It should be noted however that each of the modulation indices also corresponds to many other combinations of rf bandwidth and number of telephone channels. For example, $m = 1.19$ also applies to 600 channels in an rf bandwidth of 24 MHz, which represents the power-limited maximum capacity of the baseline fixed-satellite transponder when operating into a 16 ft baseline earth station.

The modulation indices chosen for the broadcasting-satellite examples correspond to transmission of a 525-line TV picture in FM bandwidths of 18 MHz ($M = 1.14$), 23 MHz ($M = 1.74$), and 30 MHz ($M = 2.57$). These represent appropriate bandwidths for power-limited television transmission with the baseline noise objectives adopted for individual reception, community reception, and fixed-satellite program distribution, respectively.

It is evident from Eq. (100), and from the previous discussion of sharing tactics, that the spacings shown in Fig. 27 for fixed-satellite systems could be reduced 24 percent if the total objective for interference from other satellite systems was raised to 2000 pWOp. Likewise, if the effects of noise-masking were allowed, the spacing shown for individual reception could be reduced by 50 percent, since the 43 dB noise objective for individual reception would reduce the total protection ratio by 6 dB.

The fact that non-overlapping service areas were assumed for the broadcasting-satellite service should also be emphasized, since, as previously noted, it permits a spacing reduction of over 30 percent compared with the case of overlapping service areas. Indeed, it

brings the spacings for broadcasting satellites with the 12 ft baseline community-reception antenna to a level comparable with or smaller than those needed for the fixed-satellite service using 16 ft earth stations, or even with 32 ft earth stations used for 900 or 1200 channel carriers.

Approximate Spacings for Inhomogeneous Systems

An approximate method for determining compatible intersatellite spacings when more than a single type of system shares the orbit, may be derived as follows. As in the treatment of homogeneous systems, attention is focused on interference among downlinks. An estimate is first made of the downlink protection ratio required by each type of link against interference from other links of the same type carrying co-channel signals. These are simply the limits to which the total downlink wanted-to-unwanted signal ratio must be held if the sum of the uplink and downlink interference is to meet the overall interference objective for that type of system.

Using these downlink objectives, the homogeneous spacing is computed for each type of satellite link. This provides an estimate of the minimum spacing that must be maintained between adjacent satellites carrying links of the same type. Based on the relative magnitude of the homogeneous spacings, a trial arrangement of satellite positions is postulated. For example, if there are only two kinds of links and the inhomogeneous spacings are roughly equal, an alternating deployment (XYXYXY) may be tried. On the other hand, if the homogeneous spacings are quite different, a number of the satellites with the smaller spacing might be placed in a cluster between the satellites with the larger spacing (XYYYYYXYYYYYX). The spacings between adjacent satellites, and especially between dissimilar adjacent satellites, remain to be determined.

Towards this end, each type of wanted link is considered separately. The total downlink interference to a given type of link from other downlinks, both like and unlike, is expressed as the weighted sum of reciprocal carrier-to-interference ratios indicated symbolically in Eq. (77). Although this form of summation is more "natural" when

the wanted link carries a television signal, the corresponding sum for an FDM/FM wanted signal given by Eq. (75) can be put in the same form by multiplying both sides of that equation by $R_{ii}/10^9$, where $R_{ii} = R(m_i, m_i, 0)$ is the receiver transfer characteristic for interference from an identical co-channel FDM/FM signal. In this case, the sensitivity factor and the downlink protection ratio in the sum

$$\left(\frac{X}{C}\right)_{i \text{ down}} = \sum_{j=1}^N \frac{1}{Q_{ij}} \frac{X_{ij}}{C_i} = \rho_{i \text{ down}}^{-1} \quad (115)$$

become, respectively,

$$Q_{ij} = R(m_i, m_j, v)/R_{ii} \quad (116)$$

$$\rho_{i \text{ down}} = r_i 10^9 / (R_{ii} I_{i \text{ down}}) \quad (117)$$

where $I_{i \text{ down}}$ is the downlink interference noise objective for the wanted FDM/FM link, and r_i is the factor by which it is exceeded by the total interference noise objective.

To compute intersatellite spacings that ensure the satisfaction of Eq. (115), the sum is first resolved into groups of terms each representing interference from a single type of satellite downlink. Note that each term in such a component sum will have the same Q factor. The downlink protection ratio $\rho_{i \text{ down}}$ is then similarly resolved, with the condition that the sum of the reciprocals of its "components" be equal to $\rho_{i \text{ down}}^{-1}$. When the component sums are set equal to the reciprocal components of $\rho_{i \text{ down}}$, the result is a set of equations of the same form as Eq. (115) except that in each equation, interference from only a single type of satellite is involved. Under this condition, the dominant term in the interference sum of a given equation is the one representing the contribution from the nearest satellite. By estimating the contributions of the more distant satellites as a fraction u of the contribution from the nearest satellite, the interference sum is reduced to a single term and each component equation takes the form

$$(1 - u) \frac{X}{QC} = \rho^{-1} \quad (118)$$

where X/C is the reciprocal carrier-to-interference ratio for interference from the nearest satellite, and ρ is the component downlink protection ratio for interference of this type.

In this fashion, Eq. (115) is replaced by a set of conditions on the carrier-to-interference ratios produced by the nearest unwanted satellites of each type in the trial arrangement. These equivalent single-entry equations are then solved for the required intersatellite separations as described at the beginning of this section. That is, Eq. (118) is replaced by an equation like Eq. (83) in which the single-entry protection ratio ρ_1 exceeds the component downlink protection ratio in Eq. (118) by the factor $(1 + u)/Q$.

Having determined the intersatellite spacings required to protect each satellite in the trial configuration against interference from both similar and dissimilar satellite links, a compatible set of spacings can be arrived at. In practice, the process is rather more simple than may be thought from the foregoing description, especially when only a few different types of satellites are involved. Illustrative examples will be given in the following section where the procedure is applied to the baseline systems of Sec. III.

"Exact" Spacings for Inhomogeneous Systems

The intersatellite spacings obtained by the method just described are necessarily approximate; their accuracy depends in large part on the quality of engineering judgment used in partitioning the protection ratios and in estimating the ratio of the total interference from one type of satellite to that from the nearest neighbor of that type. To verify the compatibility of a configuration of systems based on the approximate spacings and to converge on more exact spacings, a computer program capable of realistically modeling the configuration and predicting the interference levels on all links in a representative frequency band is an essential analytic tool. A program of this type is described in the Appendix and the results of its application are illustrated in Sec. VI.

VI. ILLUSTRATIVE COMPARISON OF SHARING STRATEGIES

The term "sharing strategy" was introduced in Sec. II to denote a particular plan or method for dividing the orbit-spectrum resource among the systems of two or more radio communication services. As noted there, one of the most important objectives of a sharing strategy is to ensure that the orbit and spectrum are used efficiently. It was also pointed out in Sec. II that the efficiency of a given sharing strategy depends not only on the particular combination of sharing tactics and the orbital arrangement of dissimilar satellites that characterizes the strategy but also on the parameters of the systems themselves and the signals they carry. In this section, a number of sharing strategies will be introduced and evaluated for specified combinations of the baseline systems and signals described in Sec. III.

STRATEGIES AND THEIR EVALUATION

General Categories of Strategies

The specific strategies to be examined may be divided into two basic categories. In the first, or "spectrum-division" category, the total 500 MHz allocation is divided into two sub-bands whose widths are proportional to the anticipated long-range needs of the two services. Each service is then assigned as the primary service in its sub-band; i.e., the other service is permitted to operate in that sub-band only to the extent that it does not interfere with the primary service. There is thus no frequency sharing between services (although it will still be necessary to have a strategy for intraservice sharing in each sub-band), but each service can utilize the entire visible orbital arc.

The other sharing category, called "orbit-division," permits each service to utilize the entire 500 MHz frequency allocation but avoids excessive interservice interference by deploying the satellites of the two services with appropriate angular separations in the geostationary

orbit. Examples of orbit-division range from an "alternating deployment" in which adjacent orbital positions are assigned to different services, to a "clustered deployment" in which several satellites of one service are grouped together between adjacent satellites or groups of satellites from the other service.

Just as with a spectrum-division strategy, the deployment of satellites in an orbit-division strategy should also take into account the relative long-range demands to be met by the two services. For example, if the foreseeable demand for satellite broadcasting can be met by only a few satellites, only a relatively small fraction of the orbital arc need be allocated to them.

As discussed in Sec. II, the orbital arc to be shared by domestic systems in the contiguous United States is taken as the 75 deg segment from about 60 deg to 135 deg west longitude that is visible above a 10 deg elevation angle from nearly every point in this region. Obviously, portions of the geostationary orbit lying beyond the selected 75 deg segment could be used for systems covering only a part of the country. For example, broadcasting satellites covering the western half of the United States above 10 deg elevation could be located as far west in longitude as 165 deg, and so also could fixed-satellite systems dedicated to serving only this half of the country (plus Alaska and Hawaii), for example.

It is expected, however, that the portions of the orbit beyond the 75 deg segment will not in fact be considered attractive for the fixed-satellite service; therefore, they are excluded from consideration as a fully sharable part of the orbit-spectrum resource. Nonetheless, their existence and potential utility to the broadcasting-satellite service should be borne in mind when considering how much of the sharable 75 deg arc should be assigned to this service in an orbit-division strategy.

Some of the specific deployments of interest in orbit-division strategies are illustrated schematically in Fig. 28. In all of the diagrams, the size of the symbol (dot or circle) is intended to indicate the relative eirp of the satellite. In terms of the baseline systems, small dots might indicate an eirp of 46 dBW, large dots an

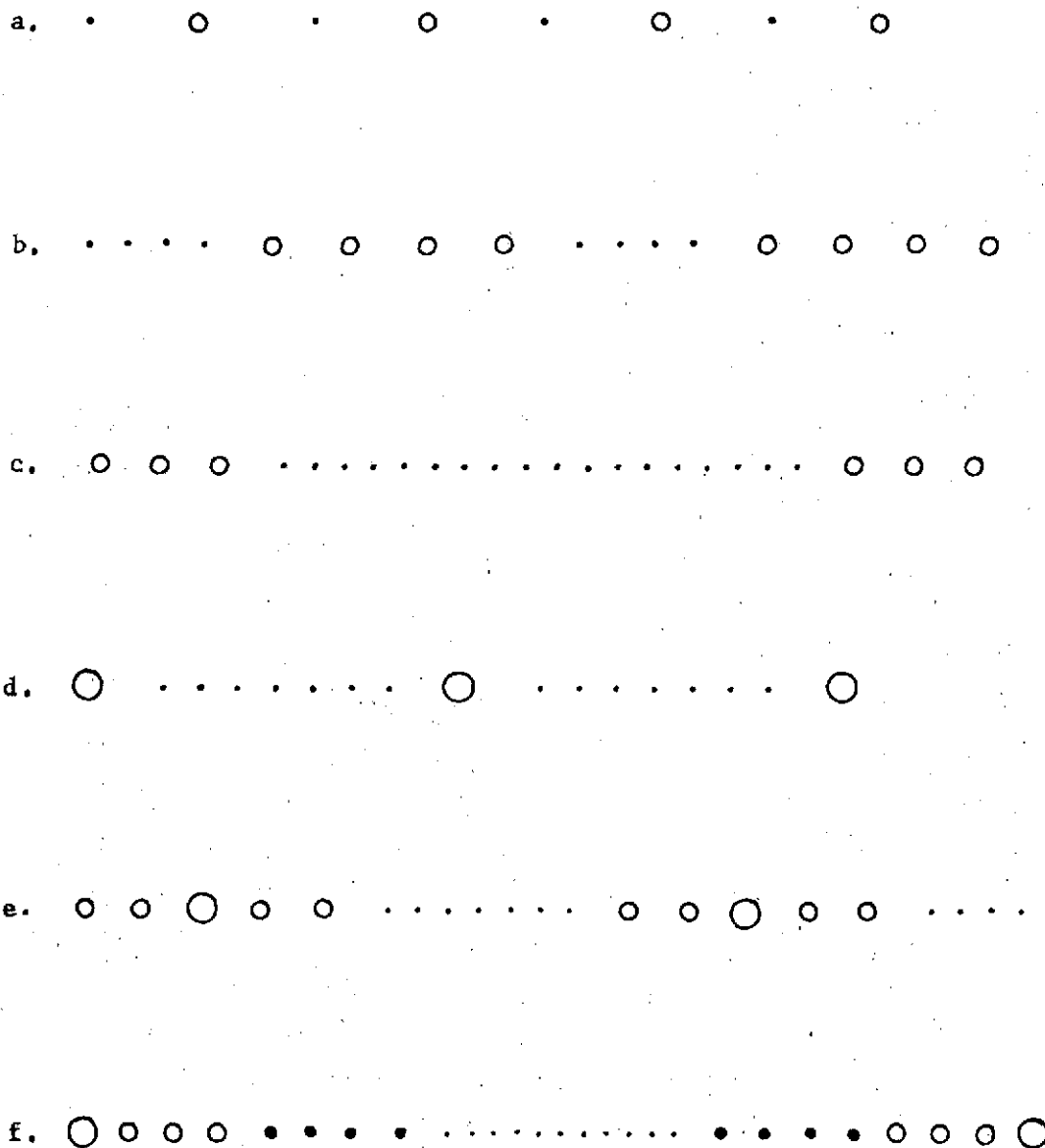


Fig. 28--Schematic examples of orbit-division deployments

eirp of 52 dBW, and small circles an eirp of 58 dBW with large circles signifying an even higher eirp. Deployments a through d thus involve only two "sizes" of satellites, with the disparity in size being greater for d than for a, b, and c.

Diagrams a through c represent forms of alternating deployment appropriate to cases where the spacing of the satellites in a spectrum-division strategy would be roughly equal. More specifically, a and b would be appropriate where the demand for each service is about equal in terms of the number of satellites required.

On the other hand, deployment c, in which the large satellites are shifted to the ends of the visible arc, might be preferable when only a comparatively few large satellites are needed to meet the anticipated demands for their service. Finally, in this group of two-size deployments, arrangement d is likely to offer most efficient orbit utilization when very large satellites are needed to provide service to very small earth receiving antennas, as would probably be the case with individual reception in the broadcasting service.

Deployments e and f, respectively, indicate cases involving three and four sizes of satellites, or to be more precise, three or four degrees of inhomogeneity (when differences in signal characteristics as well as differences in satellite eirp and earth-station antenna size are considered). Both of these deployments feature the tactic of minimizing the degree of inhomogeneity between adjacent satellites.

Orbit-Spectrum Utilization and Utilization Factors

It has been suggested that the efficiency of a sharing strategy can be measured in terms of the total communications capacity that can be realized from the orbit-spectrum resource when shared relative to the capacities that could be realized in the absence of sharing. In devising quantitative measures of such efficiency, it is first necessary to recognize that, in practical terms, the information capacity of the orbit-spectrum resource is not a fixed quantity. Capacity has meaning only relative to the parameters of the commercially feasible systems which share the resource and the fraction of the resource allocated to each type of system.

For example, in a spectrum-sharing strategy, the total number of TV channels that can be provided by broadcasting satellites will depend not only on the fraction of the spectrum allocated to them, but also on such system characteristics as the satellite eirp, the diameter and pattern of the receiving antenna, the noise temperature of the receiving system, the modulation method and modulation index used, the extent to which the service areas of different satellites overlap, the TV noise and interference performance objectives, and the degree to which polarization discrimination and carrier-frequency interleaving are used. Likewise, the number of telephone channels that can be provided by the fixed satellites will depend not only on the fraction of the spectrum allocated to them, but also on a similar list of characteristics for the systems of that service.

With an orbit-sharing strategy, the capacity for television and telephone channels becomes even more indefinite, since interference between the two types of systems can now occur and both the parameter values of one service relative to those of the other and the relative positions of the two kinds of satellites enter into the capacity calculations.

Another problem arises, even when the strategies to be compared are applied to systems with specified characteristics. Using the recommended measure of orbit-spectrum utilization (number of message channels per degree of orbit and MHz of allocated bandwidth), it is difficult to compute and compare the total orbit-spectrum utilizations achieved with the different strategies unless an arbitrary figure is assumed for the number of fixed-satellite telephone channels that are equivalent to a broadcasting-satellite television channel.

The problem of expressing orbit-spectrum capacities and utilization in absolute terms can largely be avoided, and an unambiguous, dimensionless, figure-of-merit for sharing strategies established in the manner proposed in Sec. II. To recapitulate and enlarge on that proposal, as it will be applied in this section, the dependence of orbit-spectrum capacity on system characteristics is acknowledged from the outset by specifying a set of reference or baseline systems to represent each of the services. Then, for each type of baseline system,

the capacity of the orbit and spectrum* is calculated for the condition in which the entire resource is allocated exclusively to systems of that type. This capacity will be referred to as the "homogeneous capacity" of the resource for the baseline system in question.

The utilization by each service when the resource is shared among specified baseline systems representing the two services using either spectrum- or orbit-division can then be expressed in terms of the "utilization factor," defined as the ratio of the capacity actually provided by its systems to the homogeneous capacity for such systems. For each service, the utilization factor represents the fraction of the resource utilized under the sharing strategy and should be compared to the fractional share of the resource assigned to the service. For any assigned division of the resource between the services, the total orbit-spectrum utilization factor is then the sum of the utilization factors for the two services.

The total utilization factor serves as a "figure-of-merit" for a given sharing strategy and may be displayed graphically by plotting it against the fraction of the resource allocated to one of the services. The higher the total utilization, the more efficient the strategy.

In this connection, it is interesting to note that although the utilization factor by each service approaches 100 percent only as the fraction of the resource assigned to it approaches 100 percent, the utilization factor for certain systems and orbit-division strategies can significantly exceed the fraction of the resource assigned to the systems of one service. As a result, it is possible for the total utilization factor to exceed 100 percent. This simply means that, when the resource is shared by the two services, it is possible to realize a total capacity greater than the capacity that would be expected if each service provided only a fraction of its homogeneous capacity equal to the share of the resource assigned to it.

* Either the total capacity or its normalized measure, the orbit-spectrum utilization may be used.

Homogeneous Capacity of the Orbit-Spectrum Resource

Values of the homogeneous capacities or orbit-spectrum utilizations provided by fixed- and broadcasting-satellite systems are needed for computing utilization factors.

The general expression for the homogeneous orbit-spectrum utilization in channels per MHz per degree is

$$U = \frac{n}{W\phi_h} \quad (119)$$

It can be expressed in terms of basic system parameters using the equations for homogeneous spacing ϕ_h from Sec. V and the ratios W/n of rf bandwidth to number of channels given in Sec. III. Thus, for an n-channel FDM/FM fixed-satellite system with rms modulation index m , the bandwidth per channel is given by Eq. (7) and the homogeneous spacing by Eq. (100). With these substitutions, the homogeneous utilization becomes

$$U_F = \frac{(I_o f(n)/r_F)^{0.4}}{48.3} \frac{(1 + 9m^3)^{0.4}}{\sqrt{\Lambda} m + 1} D^{0.8} \quad (120)$$

where the various parameters were defined in connection with the equations cited. For the common case where $n \geq 240$ telephone channels, $I_o = 1000$ pWop, $\Lambda = 10$, and r_F is given by Eq. (110), the result is

$$U_F = 1.19 \frac{(1 + 9.5 m^3)^{0.4}}{3.16 m + 1} D^{0.8} \quad (121)$$

As an example appropriate to the baseline fixed-satellite system the values $m = 1$ and $D = 32$ ft, yield a utilization of about 10 channels per MHz per degree. This corresponds to a total capacity of 324,000 channels for 75 deg of arc and the net $12 \times 36 = 432$ MHz of signal bandwidth typically available from a 500 MHz band of frequencies.

For a TV/FM broadcasting-satellite system with modulation index M and nonoverlapping service areas, W/n is given by Eq. (15), and ϕ_h by Eq. (108) or Eq. (109); the resultant orbit-spectrum utilizations

for community and individual reception are, respectively,*

$$U_C = \frac{0.00408}{(qr_C)^{0.4}} \frac{M^{0.8}}{M+1} D \quad (122)$$

$$U_I = \frac{0.00219}{(qr_I)^{0.5}} \frac{M}{M+1} D \quad (123)$$

where the factor q is included so that, if desired, the effects of interference masking by noise can be taken into account. When $q = 1$ (no interference masking) and r_C and r_I are given by Eqs. (113) and (114), the numerical factors in the equations for U_C and U_I are 0.00357 and 0.00208, respectively.

For example, with values of $M = 1.74$ and $D = 12$ ft appropriate to the baseline community-reception system, the utilization is 0.024 channels per MHz per degree, which is equivalent to a total capacity of about 778 TV channels for 75 deg of arc and 432 MHz of bandwidth. In contrast, the baseline individual-reception system ($M = 1.14$, $D = 3$ ft) provides a utilization of only 0.0033 channels per MHz per degree, corresponding to a total capacity of about 108 TV channels.*

Combinations of Baseline Systems to be Analyzed

Almost all of the important features of an orbit-spectrum sharing strategy can be evaluated by applying it to reference cases in which each service is represented by a single type of baseline system. Three basic combinations of baseline systems, identified as Case 1, Case 2, and Case 3, have been selected for analysis.

In Case 1, the baseline systems representing the two services are deliberately chosen to have widely different parameters to illustrate the effect of large inhomogeneities in satellite eirp, earth-station figure-of-merit, and channel bandwidth. Referring to Table 8, the

* As noted in connection with the equations for ϕ_h , the result for individual reception is likely to be overoptimistic for comparatively low modulation indices because the CCIR-suggested upper limit of 30 dB on earth-station antenna discrimination (see pattern I in Fig. 17) was not allowed for.

fixed-satellite, large-terminal baseline system (FL) is used to represent the fixed-satellite service. This system employs a 46 dBW satellite in conjunction with an earth station having a 32 ft antenna. The broadcasting-satellite service is represented by the 58 dBW satellite and 3 ft diameter receiving installation listed in Table 8 for the individual-reception baseline system (BI).

In Case 2, the fixed-satellite baseline systems of Case 1 share the orbit and spectrum with the baseline broadcasting-satellite community-reception systems (BC). The latter uses 52 dBW satellites and 12 ft ground receiving antennas. This combination is probably more closely representative of the broadcasting-satellite systems likely to be developed for U.S. applications.

Finally, in Case 3, the baseline community-reception system of Case 2 is paired with the baseline fixed-satellite system (FS) using the "small," or 16 ft, earth-station antenna. This also represents a sharing combination likely to occur in U.S. domestic applications, and it is the most nearly homogeneous mix of fixed- and broadcasting-satellite systems considered.

Combinations of RF Signals To Be Analyzed

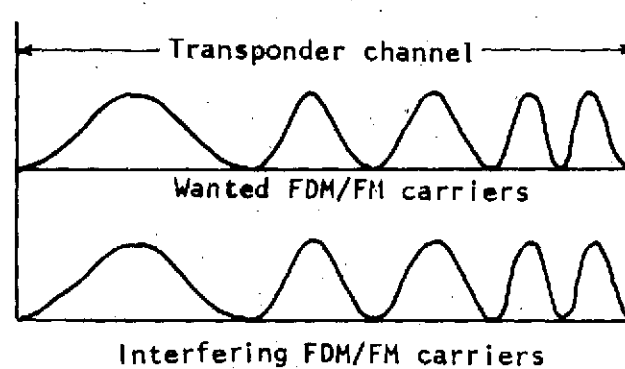
For each of the three basic cases just described, there are a number of subcases to be considered for each strategy. One reason is that the effectiveness of a sharing strategy depends not only on the equipment parameters of the systems to which it is applied but also on the characteristics of the signals on the links supported by those systems. The parameters of the baseline systems were chosen to permit their use with a variety of different signals. This is especially true for the fixed-satellite systems. For example, using the large earth station assumed in Case 1, a given transponder can be used for a single 1200 channel link or for a number of links with capacities ranging from one to several hundred channels. Therefore, it would appear necessary to consider a number of the foreseeable interfering signal combinations that might arise in practice with FDM/FM links carrying different numbers of channels with different eirps per carrier, and using different carrier-frequency plans.

Fortunately, a preliminary analysis suggests that the number of cases to be considered could be reduced to a single one, provided that certain reasonable rules are followed in the choice of modulation indices and eirps for the various carriers. The rules in question are that the modulation indices of all carriers be those corresponding to minimum-power or power-limited operation as discussed in Sec. III, and that on all satellites, the relative carrier levels be adjusted so that eirp for each carrier is proportional to the associated per-carrier EG/T requirement. Table 3 illustrates a set of such modulation indices and EG/T requirements for the baseline system noise and threshold margin objectives shown in Table 2.

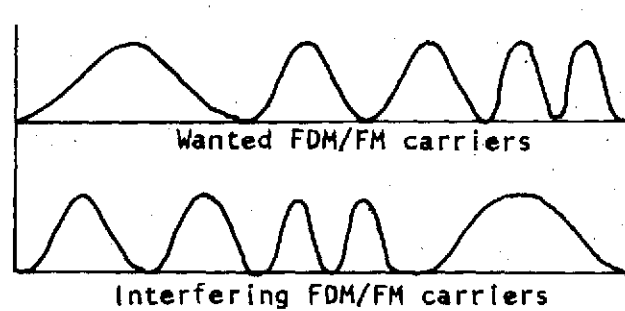
The reason that only one case need be considered if these rules are followed is that the intersatellite spacings which ensure compatible sharing with co-channel FDM/FM carriers of one size^{*} are equally applicable to carriers of all sizes, without regard to how they are arranged in frequency. In particular, inter-satellite spacings can be computed with the assumption of co-channel single-carrier-per-transponder operation using the largest size carrier for which power-limited operation within the transponder bandwidth is possible.

To explain how the rules in question lead to this conclusion, consider the three interference situations depicted schematically in Fig. 29. Consider first the set of wanted and interfering carriers shown in Fig. 29a. Here, the carriers are arranged within the transponder channel so that each one faces only co-channel interference from a carrier of like size. With this condition, the receiver transfer characteristic R that determines the interference vulnerability of a carrier will depend only on the modulation index m and the size n of the carrier as given in Eq. (38). However, it may be shown that the rule just given for choosing modulation indices leads to a dependence of m on n which makes R almost exactly the same for all carriers, regardless of size. It follows that the individual interference contributions, as given by Eqs. (79) and (81), and hence the satellite

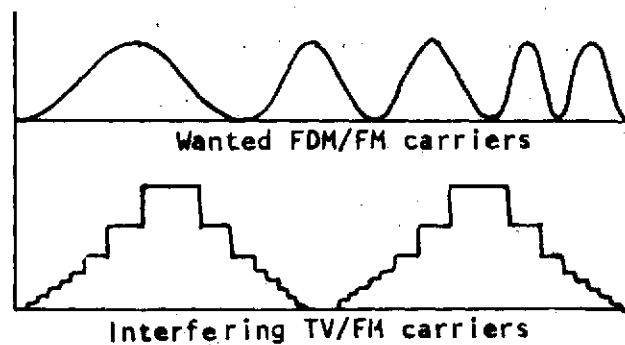
* The term "carrier size" refers to the number of channels in the baseband which modulates the carrier.



a. Carrier sizes and frequencies restricted to co-channel interference between like carriers



b. No restrictions on carrier sizes and frequencies



c. Interservice interference

Fig. 29--Schematic illustration of interference to FDM/FM carriers

spacings required to keep the total interference on the links within specified limits will also be independent of carrier size.

In the interference situation shown in Fig. 29b, the restriction on the arrangement of carriers having different sizes within the transponder bandwidth is removed. The receiver transfer characteristic now depends on the sizes and modulation indices of both the wanted and interfering carriers and on the difference between the carrier frequencies. Moreover, calculation of the interference contributions must also take into account the difference ΔE between the eirps of the wanted and unwanted carriers when they differ in size. However, the combined effect of the rules governing modulation indices and carrier power is to prevent the quantity $\Delta E - 10 \log R$ in the equations for the interference contributions from exceeding its value for co-channel interference between carriers of the same size. Hence the interference with carriers of unequal size and arbitrary frequency plan is no greater than with co-channel carriers of equal size, and the spacings which permit compatible operation in the latter case also do so in the former.

Finally, consider the case of interservice interference shown in Fig. 29c. Here, a pair of TV/FM carriers from a broadcasting satellite are interfering with a set of FDM/FM carriers in the same transponder channel. The receiver transfer characteristic R given by Eq. (29) depends only on the modulation index m and size n of the wanted signal and on the frequency offset of the unwanted signal. Again, interference is worst for the co-channel case, and it can be shown that the dependence of R on m and n is such that the rules for choosing modulation indices and carrier powers as a function of carrier size ensure that the spacings computed for co-channel operation with any given size carrier will protect carriers of all other sizes and frequency offsets.

On the basis of the foregoing arguments, it would appear to be sufficient to investigate sharing strategies using only a single carrier size on the fixed-satellite system--specifically, one of the set of carriers whose modulation index corresponded to minimum power operation. For example, a 900 channel carrier with 36 MHz bandwidth

would be appropriate for the baseline fixed-satellite system of Case 1, and a 600 channel signal in a 24 MHz bandwidth for the fixed-satellite system of Cases 2 and 3. But as a practical matter, there may be sound economic reasons for operating with either higher or lower modulation indices and eirps than suggested by the rules just discussed.

For example, on a single-carrier-per-transponder basis, the fixed-satellite system of Case 1 has sufficient power to support up to 1500 channel carriers in bandwidth-limited operation. Such operation may be economically attractive because fewer satellites are needed for a given total system capacity, even though the correspondingly lower modulation index leads to wider satellite spacings and slightly less efficient orbit-spectrum utilization. To investigate the effects on sharing of using modulation indices chosen by different rules, additional subcases are included. In Case 1, for example, sharing strategies are analyzed for carrier sizes of 600 and 1200 channels as well as for the 900 channel minimum-power carrier.

Analytic Approach

The same general analytic procedure is used for evaluating sharing strategies in each of the cases and subcases described above. The procedure consists of the following 6 steps:

1. The spacing, orbit-spectrum utilization, and total capacity for exclusive occupancy, assuming co-channel, co-polarized links, are calculated for each of the representative baseline systems using equations such as Eqs. (100), (108), and (109) for the spacings.
2. Using these data, the utilization factors for each service and the total utilization factor are calculated for the spectrum-division strategy as a function of the share of the spectrum, and hence of the orbit-spectrum resource, assigned to each of the services.
3. Based on the homogeneous spacings calculated for the baseline systems in Step 1, trial orbit-division satellite deployments of the type shown in Fig. 28 are postulated

along with carrier-frequency plans appropriate to the signal bandwidths assumed for each service, using the guideline discussed in connection with that figure. As in the case of the spectrum-division strategy examined in Step 2, it is assumed that neither frequency interleaving nor cross polarization is employed on the links of a given service. For each satellite deployment, the required intersatellite spacings are calculated using the approximation procedure for inhomogeneous systems described at the end of Sec. V. Note that although no frequency interleaving was assumed within a service, the spacing calculations must take into account the frequency offsets that may occur with interservice interference.

4. The interference compatibility of each of the trial orbit-division strategies is tested for the baseline ground segments described in Sec. III by applying the computer simulation program described in the Appendix. In particular, the interference level computations for each strategy are repeated for a combination of intersatellite spacings which brackets the approximate values calculated in Step 3. The "final" values of intersatellite spacings adopted for a given strategy are then inferred from an inspection of the computer simulation results.
5. For selected orbit-division strategies, the single-service and total-utilization factors are calculated as a function of the share of the orbit, and hence of the orbit-spectrum resource, assigned to each service. The results for these orbit-division strategies are plotted for comparison with each other and with the results obtained at Step 2 for the spectrum-division strategy.
6. Finally, the enhancement of orbit-spectrum utilization that can be achieved by modifying the various sharing strategies to include additional sharing tactics is investigated. Predictions based on parametric analysis are verified where appropriate with the aid of computer simulation.

CASE 1: SHARING BETWEEN FIXED-SATELLITE SYSTEMS WITH LARGE
TERMINALS AND BROADCASTING-SATELLITE SYSTEMS FOR INDIVIDUAL
RECEPTION

Equipment and Signal Parameters

As observed earlier, this case is of particular interest because of the large differences between the parameters of the baseline systems FL and BI which represent the two services. A complete listing of these parameters was given in Table 8. A recapitulation of the principal downlink parameters is given in Table 12, together with the assumptions regarding downlink antenna pattern envelopes, the bandwidths of the rf channel and of the TV/FM and FDM/FM carriers, the carrier frequencies, and both the total and the downlink objectives for thermal noise and interference.

Note that the interference objective for the broadcasting-satellite service applies to interference between identical, co-channel signals of the indicated bandwidth with no allowance for interference-masking ($q = 1$). Also note that, with the indicated selection of carrier frequencies, each FDM/FM link suffers interference from two TV/FM carriers whose carrier frequencies are displaced 10 MHz from that of the FDM/FM carrier. For reasons discussed earlier in this section, three carrier sizes (600, 900, and 1200 channels) are selected for the FDM/FM links of the fixed-satellite service.

For both services, the CCIR pattern envelopes indicated in Table 12 assumed the use of sidelobe reduction techniques on the satellite antennas but not on the earth-station antennas. Moreover, for the ground receiving installations in the broadcasting-satellite service, the CCIR pattern envelope for community reception was used instead of the pattern suggested for individual reception. This choice was made because, with a 28.4 dB downlink protection ratio, the 30 dB discrimination limit of the latter pattern is insufficient to permit interference from more than one other broadcasting satellite, or from any combination of fixed and broadcasting satellites.

Table 12
PARAMETERS FOR CASE 1 BASELINE SYSTEMS

Quantity	Symbol	Unit	Broadcasting-Satellite System (BI)	Fixed-Satellite System (FL)
<u>Satellite Transmitter</u>				
Transmitter power	P	W	166	38
Antenna beamwidth	θ_o	deg	1.7 x 3.3	3.5 x 7
Antenna pattern ^a	-	-	B-B	F
eirp	E	dBW	58	46
<u>Earth Station Receiver</u>				
Receiving antenna diameter	D	ft	3	32
Antenna pattern ^b	-	-	C	F
System temperature	T	°K	500	250
Figure-of-merit	G/T	dBW/°K	12	35
<u>Signals</u>				
Carrier type	-	-	TV/FM	FDM/FM
Signal bandwidth	W	MHz	18	36
Channel spacing	-	MHz	20	40
Uplink carrier frequencies	-	GHz	14.01, 14.03	14.02
Downlink carrier frequencies	-	GHz	11.71, 11.73	11.72
<u>Message Objectives</u>				
Total thermal noise ^c	$\left(\frac{S}{N}\right)_o, N_o$	dB, pWOp	43	5000
Downlink thermal noise ^c	$\left(\frac{S}{N}\right)_{down}, N_{down}$	dB, pWOp	44	4000
Total interference ^c	ρ_o, I_o	dB, pWOp	28.3	1000
Downlink interference ^c	ρ_{down}, I_{down}	dB, pWOp	28.4	590

^aSee Fig. 18 for code.

^bSee Fig. 17 for code.

^cThe first entry in the symbol and unit columns applies to system BI, the second entry to System FL.

Spacings and Capacities for Exclusive Allocations

The satellite spacings, orbit-spectrum utilizations, and total capacities of the orbit-spectrum resource corresponding to exclusive use by the baseline systems are displayed in Table 13. The significance of the tabulated values is illustrated by the following observations.

If the entire resource were allocated exclusively to fixed-satellite baseline systems with 1200 channel links, for example, a spacing of 3 deg could be achieved. At this spacing, 26 satellites could be accommodated and since each satellite has a capacity for 12 40 MHz rf channels, each carrying 1200 channels, the capacity per satellite is 14,400 channels and the total capacity of all satellites is $26 \times 14,400 = 374,400$ simplex telephone channels. This capacity will be the reference for calculating orbit-spectrum utilization factors for orbit- and spectrum-division sharing strategies involving 1200 channel fixed-satellite systems of the type assumed. The orbital configuration is shown schematically in Fig. 30.

If the resource were allocated to fixed-satellite systems with 900 or 600 channel links, the spacing between satellites could be reduced to 2.0 and 1.1 deg, respectively. However, as noted in the discussion of sharing tactics in Sec. V and confirmed by the results shown in Table 13, these reductions are not accompanied by similarly dramatic increases in capacity or utilization and, in any case, require the use of much larger numbers of satellites. For example, the 29 percent increase in utilization gained in going from 1200 to 600 channels per carrier requires the launch of 2.6 times as many satellites.

If the entire orbit-spectrum resource were to be allocated to broadcasting-satellite systems of the type chosen for Case 1, the minimum orbital spacing of 8.8 deg permits 9 satellites to be accommodated in the assumed 75 deg orbital arc. Since each satellite has a capacity of $500/20 = 25$ television channels, the total capacity of the orbit and spectrum for this kind of satellite broadcasting is $9 \times 25 = 225$ television channels. This capacity for a 100 percent assignment to the broadcasting-satellite service is used as the reference for calculating the utilization factors possible in orbit- and

Table 13

SATELLITE SPACINGS AND ORBIT-SPECTRUM CAPACITIES
AND UTILIZATIONS FOR EXCLUSIVE OCCUPANCY BY
CASE 1 BASELINE SYSTEMS (see Table 12)

Quantity	Symbol	Unit	Broadcasting-Satellite System (BI) ^c	Fixed-Satellite System (FL)		
Number of channels per carrier	n	-	1	600	900	1200
Modulation index	M,m	-	1.14	1.94	1.19	0.813
Homogeneous spacing	φ_h	deg	8.8	1.14	2.0	3.0
Number of satellites ^a	-	-	9	67	38	26
Capacity per satellite ^a	-	Channels	25	7,200	10,800	14,400
Total capacity ^a	-	Channels	225	482,400	410,400	374,400
Orbit-spectrum Utilization ^b	U	$\frac{\text{Channels}}{\text{MHz deg}}$	0.0060	12.9	10.9	10.0

^aFor 75 deg of orbit and $12 \times 36 = 432$ MHz of spectrum.

^bThe values in this table will differ slightly from those calculated using Eqs. (121) and (122) because of rounding errors and because they were calculated using the discrete numbers of satellite shown in the table.

^cNote from Table 12 that system BI assumes the use of the antenna pattern for community reception rather than for individual reception.

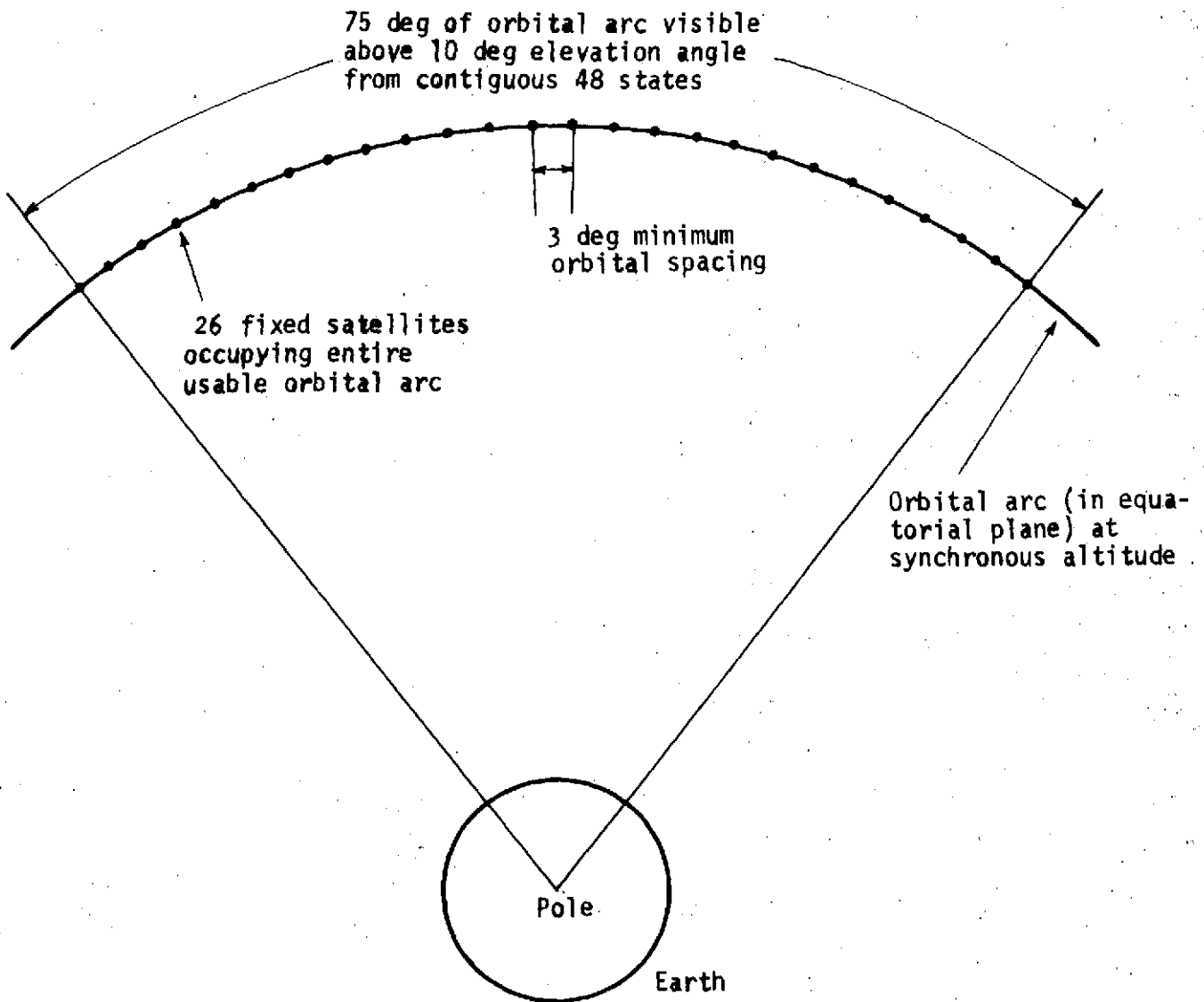


Fig. 30--1200 channel baseline fixed-satellite system for Case 1
with exclusive allocation of orbital arc using
minimum spacing

spectrum-division strategies with this baseline system. The orbital configuration is shown schematically in Fig. 31.

Spectrum-Division Strategy

As previously noted, the effectiveness of a sharing strategy can be displayed by plotting the utilization factor for each service versus the fraction of the spectrum resource assigned to it. For any given assignment, the utilization factor is simply the achievable capacity or orbit-spectrum utilization relative to that for an exclusive allocation. With spectrum division, each service has the entire orbital arc, so the fraction of the resource allocated to one service is just the fraction of the total 500 MHz bandwidth allocated to it.

Since there is no possibility of interservice interference with a spectrum-sharing strategy, each service can use the same number of satellites as it would if it enjoyed exclusive occupancy of the resource. As a result, the utilization factor for each service will closely match its share of the frequency band. Since the band is divided into discrete channels, the utilization factor for a service will increase in steps as the percentage of the spectrum assigned to it increases.

This is illustrated for the broadcasting-satellite service by the curve ascending to the right in Fig. 32. As expected, the utilization factor equals the percent of spectrum assigned whenever that amount of spectrum is equal to an integral number of channels. A similar stepwise utilization applies for the fixed-satellite service regardless of the number of channels per link as shown by the curve descending to the right, except that the horizontal step size is double that for the broadcasting-satellite service.

It is evident that, with spectrum sharing, the utilization factor for either service is equal to or only a few percent less than the share of the resource assigned to that service. This is true regardless of the relative size of the shares so long as it includes at least one channel. As a result, the total utilization factor with spectrum sharing remains close to 100 percent as shown by the upper curve in Fig. 32; it attains 100 percent whenever the television and telephone channels completely occupy the allocated spectrum.

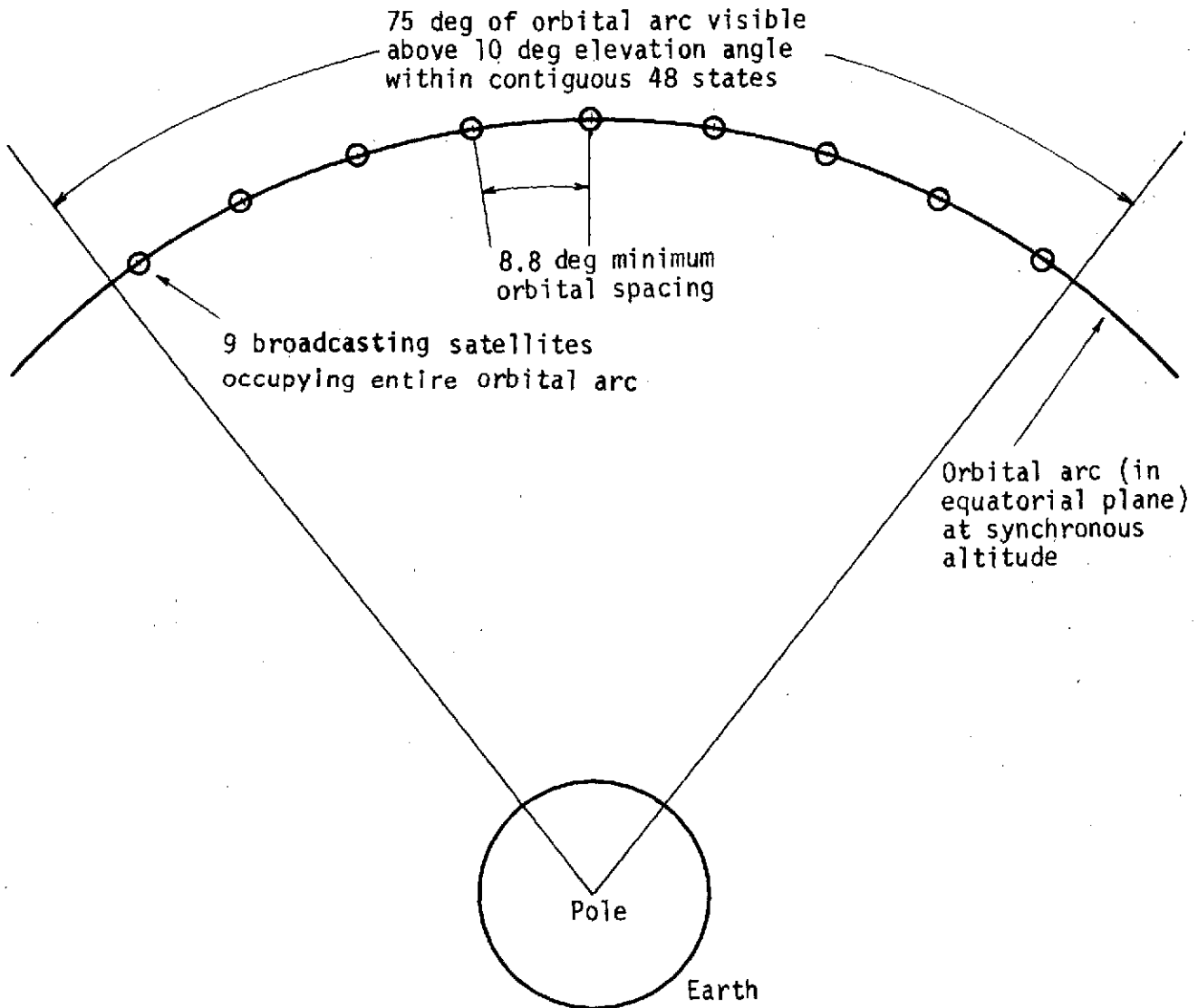
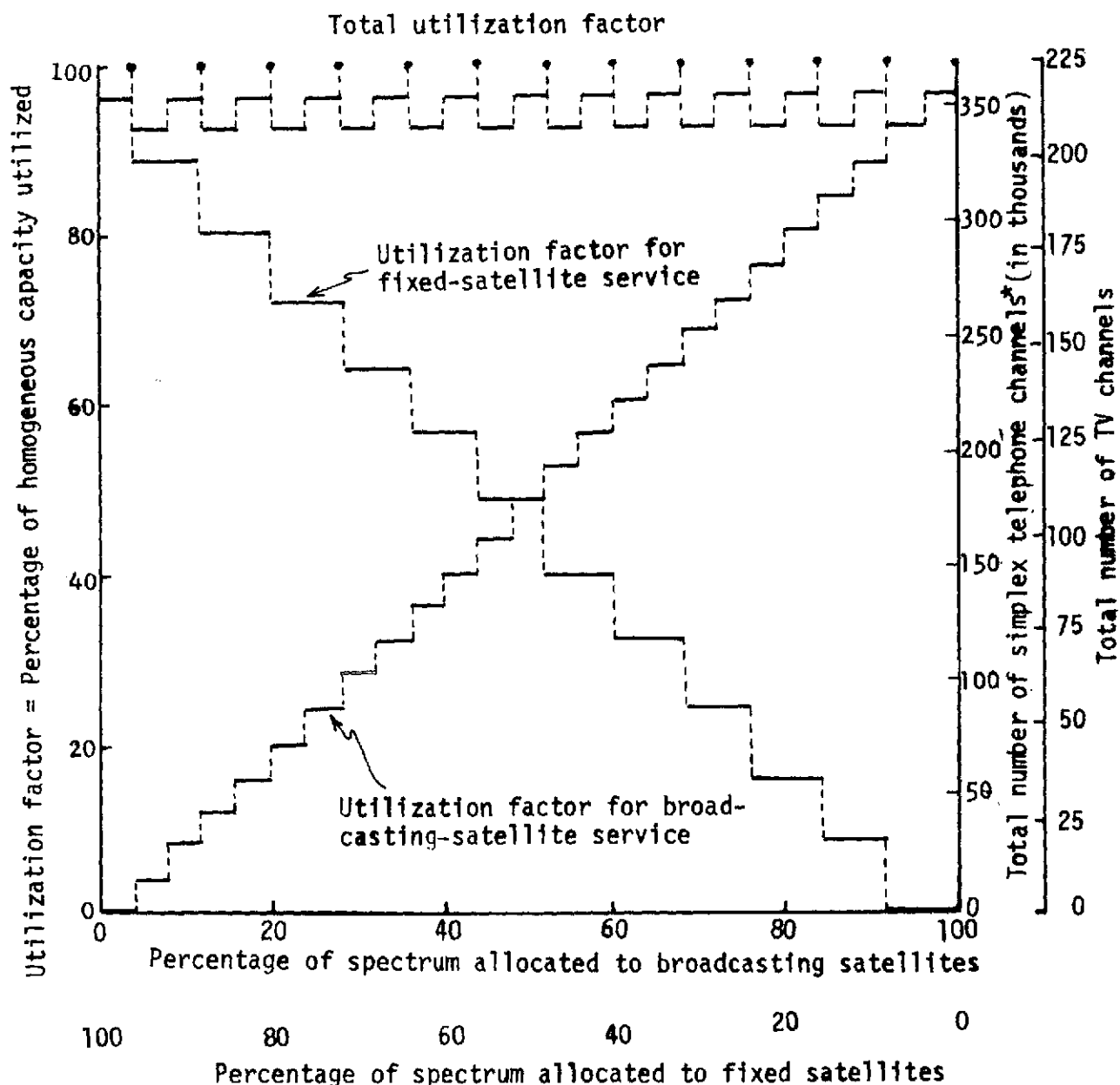


Fig. 31--Baseline broadcasting-satellite system for Case 1 with exclusive allocation of orbital arc using minimum spacing



* Numbers shown are for 1200 channel links. For 900 channel links, increase numbers by 10 percent. For 600 channel links, increase numbers by 29 percent.

Fig. 32--System capacity utilization for spectrum division between 36 MHz, 1200 channel, fixed-satellite links and 18 MHz, individual-reception, TV broadcasting links

To judge whether the utilization factors obtained through such spectrum-division are in fact adequate to meet potential demand, it should be noted that the ordinate in Fig. 32 may also be given in terms of the numbers of broadcast-satellite television channels and fixed-satellite telephone channels. The values illustrated for the fixed-satellite service on the right-hand scale of the plot are for 1200 channel links. As noted in the figure, these capacities should be increased by 10 percent and 29 percent for 900 and 600 channel links, respectively.

The effect of changing the interference objectives--for example by doubling the interference noise permitted in telephone channels, or reducing the broadcasting-satellite protection ratios by 6 dB to allow for the making of interference effects by noise--may be displayed in a similar fashion. For any given number of channels, if I_0 is increased to $k \cdot 1000$ pWOp, the fixed-satellite capacity scale should be increased by a factor $k^{0.4}$. Similarly, if the protection ratio is reduced 6 dB, the broadcasting-satellite capacity scale should be increased by 74 percent.

Orbit-Division Strategies

With an orbit-division strategy, each service has the entire spectrum, so that the fraction of the resource assigned to a service is equal to the fraction of the orbital arc "occupied" by the satellites of that service. This fraction in turn depends on how the two kinds of satellites are deployed in orbit. For the baseline systems assumed for Case 1, the fact that the homogeneous spacings for the broadcasting satellites are significantly larger than those for the fixed satellites suggests that clustered deployments like those shown in Figs. 28c and 28d should be considered.

To determine the intersatellite spacings that are appropriate for such deployments, however, it is necessary to make calculations of the type outlined at the end of Sec. V. For example, in the deployment of Fig. 28d, it is necessary to determine for each of the broadcasting satellites (represented by the circles in the figure) how far away the nearest fixed satellite (represented by the dots) must be,

as well as how far away the next adjacent broadcasting satellite must be, so that the ratio of the wanted TV/FM signal power to the aggregate unwanted signal power will not drop below the protection ratio. Similar calculations must likewise be made for each fixed satellite.

The calculations are complicated by the fact that all of the spacings are interdependent; thus the spacing that must be maintained between a broadcasting satellite and the nearest fixed satellite also depends on the spacing between adjacent fixed satellites. Nonetheless, as explained in Sec. V, approximate solutions may be obtained by first partitioning the downlink protection ratio into components for each type of interfering satellite, and then estimating the total interference from satellites of that type in terms of the interference from the nearest such satellite.

Alternating Deployment with 1200 Channel Fixed Satellites (Subcase 1a). Before summarizing all of the deployments considered and the results obtained, the computational procedure will be illustrated in some detail to derive a particular deployment of broadcasting satellites with fixed satellites that carry 1200 telephone channel links. In this case, the homogeneous spacings for fixed satellites are 3.0 deg and those for broadcasting satellites are 8.8 deg, as shown in Table 13. If fixed satellites are to be clustered between adjacent broadcasting satellites, the latter will have to be moved apart (compared with their homogeneous spacing) to reduce interference from broadcasting satellites by an amount equal to the added interference from the clusters of fixed satellites. It seems reasonable to require that the increase in spacing between adjacent broadcasting satellites be such that the interference contributions from the two kinds of satellites in the clustered deployment are equal. Since the downlink protection ratio for homogeneous interference to the broadcasting satellites was 28.4 dB (see Table 12), this corresponds to component protection ratios of 31.4 dB.

Because the broadcasting links are all alike and the broadcasting service areas were assumed not to overlap, the interference sum in the component equation for interference from other broadcasting satellites is given by the expression on the right side of Eq. (105).

provides a utilization factor of 6/9 or 67 percent for a total of 150 television channels from its half of the orbit-spectrum resource, whereas the fixed-satellite service provides a utilization factor of 6/26 or 23 percent for a total capacity of 86,400 simplex telephone channels, from its half. The total utilization factor is, of course, 90 percent.

This total utilization factor is not drastically worse than the 93 to 100 percent values characteristic of spectrum division. However, the inflexibility of the assignable shares and the fact that the broadcasting-satellite service utilizes its share almost three times as efficiently as the fixed-satellite service (when the heavier demand is likely to be for the latter service) make alternating deployment one of the less interesting orbit-division strategies.

Clustered Deployment with 1200 Channel Fixed Satellites
(Subcase 1b). Although $\phi_{BB} = 11.4$ deg was the spacing between broadcasting satellites that reduced interference between such satellites to one-half of the value at the homogeneous spacing, there is no reason that wider spacings could not be used. In particular, if the spacing is widened to more than the larger of the angles $(2\phi_{BF} + \phi_{FF})$ and $(2\phi_{FB} + \phi_{FF})$, a cluster of two fixed satellites can be inserted between adjacent broadcasting satellites. This configuration, which will be referred to as Case 1b, was also examined parametrically and by computer simulation. With the condition that the output interference noise I not exceed 1000 pWop for the worst fixed-satellite channels, and that the carrier-to-interference ratio C/X will exceed 28.4 dB at broadcasting-satellite service area boundaries, the following values were found to be near optimum in the sense that the worst channels in both services were operating at or near their interference limits.

$$\phi_{FF} = 2.9 \text{ deg}$$

$$\phi_{BF} = 7.2 \text{ deg}$$

$$\phi_{BB} \geq 2 \times 7.2 + 2.9 = 17.3 \text{ deg}$$

The third condition is important. It suggests that so long as the first two conditions are maintained, ϕ_{BB} can be made large enough to permit clusters consisting of more than two fixed satellites to be placed between adjacent broadcasting satellites. This possibility permits considerable flexibility in the relative number of satellites that can be deployed. Although the maximum number of broadcasting satellites is 5 (sharing the 75 deg orbital segment with either 9 or 10 fixed satellites), smaller numbers of broadcasting satellites can be deployed with correspondingly larger numbers of fixed satellites until with only one broadcasting satellite, from 23 to 25 fixed satellites (in unequally sized clusters) can share the orbit. A typical orbit-division deployment of this type is shown schematically in Fig. 33.

To compute the fractions of the nominal 75 deg of orbit occupied under these variations of Subcase 1b, each broadcasting satellite is considered to occupy an arc equal to $2\phi_{BF} - \phi_{FF} = 11.5$ deg and each fixed satellite a 2.9 deg arc except for satellites at the ends of the arc, which are considered to occupy arcs only half as wide as these.

With the foregoing assumptions, the utilization factors for the two services were determined as a function of the assigned shares of the orbit. The result for the broadcasting-satellite service is shown by the curve ascending to the right in Fig. 34; that for the fixed-satellite service by the curve descending to the right. The total utilization is shown by the curve at the top of the figure.

Comparison of the curves for orbit division in Fig. 34 with those for spectrum division in Fig. 32 reveals several important similarities and distinctions. Like the spectrum-division curves, the utilization factor proceeds in discrete steps, since both the share of the orbit occupied by each service and the number of channels provided by each remains essentially constant so long as the number of each kind of satellite in the orbit remains the same. A sudden decrease in occupied orbit with no decrease in the number of satellites or in utilization factor occurs for the broadcasting-satellite service when an increase in spacing between broadcasting satellites places this type of satellite at the ends of the 75 deg arc. A further increase

Setting this equal to the reciprocal component protection ratio and using the assumed sidelobe pattern (C), the required spacing ϕ_{BB} between adjacent broadcasting satellites in a clustered deployment is found to be 11.4 deg.

For reasons explained in Sec. V, the component equation for finding the spacing ϕ_{BF} from a broadcasting satellite to the nearest fixed satellite will have the form of Eq. (118) where, in the present case, ρ is the component downlink protection ratio for the interference between homogeneous broadcasting satellites, Q is the sensitivity factor which adjusts ρ to apply to interference from the frequency-offset fixed-satellite interfering signals, and u is an estimate of the ratio of unwanted signal power from all fixed satellites to that from the nearest one. As was also explained in Sec. V, the result of expressing X/C in Eq. (118) in terms of system and path parameters is an equation like Eq. (83) but with ρ_1 replaced by $(1 + u) \rho/Q$. Setting the parameters in this equation to their Case 1 values ($10 \log \rho = 31.4$ dB, $\Delta E = -12$ dB, $10 \log Q = -1.3$ dB, $10 \log (1 + u) = 5$ dB), and neglecting the path loss and satellite antenna discrimination terms, the net angular discrimination required of the ground receiving antenna of the broadcasting-satellite system is 25.7 dB. The corresponding geocentric spacing ϕ_{BF} is 6.8 deg.

Since this value of ϕ_{BF} is more than half of ϕ_{BB} , it is apparent that no cluster of fixed satellites can be placed between adjacent broadcasting satellites without increasing ϕ_{BB} still further. On the other hand, if the cluster were replaced by a single fixed satellite (corresponding to the alternating deployment of Fig. 28a), the value of u could be revised to make $10 \log (1 + u) = 3$ dB, and the required ground antenna discrimination would drop to 23.7 dB, corresponding to $\phi_{BF} = 5.6$ deg. This is slightly less than half of ϕ_{BB} , so from the point of view of the broadcasting satellites, an alternating deployment with a spacing of 5.7 deg would be feasible.

It remains to determine whether such a separation in an alternating deployment would protect the fixed satellites against interference from both broadcasting satellites and other fixed satellites.

Proceeding in the same manner as just explained for broadcasting satellites, and noting that the equivalent sensitivity factors and protection ratios are given by Eqs. (116) and (117), respectively, the required spacings turn out to be $\phi_{FF} = 3.9$ deg and $\phi_{FB} = 6.5$ deg. Here ϕ_{FF} is the minimum permissible spacing between adjacent fixed satellites required to protect one of them against interference from all the rest, and ϕ_{FB} is the minimum spacing between a fixed satellite and the adjacent broadcasting satellite that will protect the former against interference from all of the broadcasting satellites. Since the calculated value of ϕ_{FB} exceeds that for ϕ_{BF} , the former becomes the minimum spacing that must be maintained in an alternating deployment of the two systems.

Extrapolation of a computer simulation of this case for spacings in the order of 6.5 deg suggests that, if the carrier-to-interference ratio is to exceed the total protection ratio at the boundaries between service areas, the minimum spacing would, in fact, have to be increased to 7 deg. The same simulation also indicated that an intersatellite spacing of 5.9 deg would have been sufficient to keep interference in the worst channel of the fixed satellite links below 1000 pWOp. However, it should be noted that in this computer simulation, the broadcasting satellites were located on approximately the same longitudes as the centers of their service areas (see Table 10). As explained in Sec. V, the effect of crossed-path operation would have been to raise the carrier-to-interference ratios to the extent that the smaller spacings could probably have been used.

The alternating deployment just considered, which will be referred to as Case 1a, may be viewed as a special case of a clustered deployment where the number of satellites in the cluster is one. In such a deployment, all of the spacings between adjacent satellites are of necessity equal and the total number of satellites in each case differs by one at the most. Thus there is no flexibility for assigning unequal shares of the orbit to the services; each has a nearly 50 percent share. At the nominal 7 deg spacing inferred from the computer simulation, there can be no more than 6 satellites of each kind in a 75 deg segment of the geostationary orbit. Thus, the broadcasting-satellite service

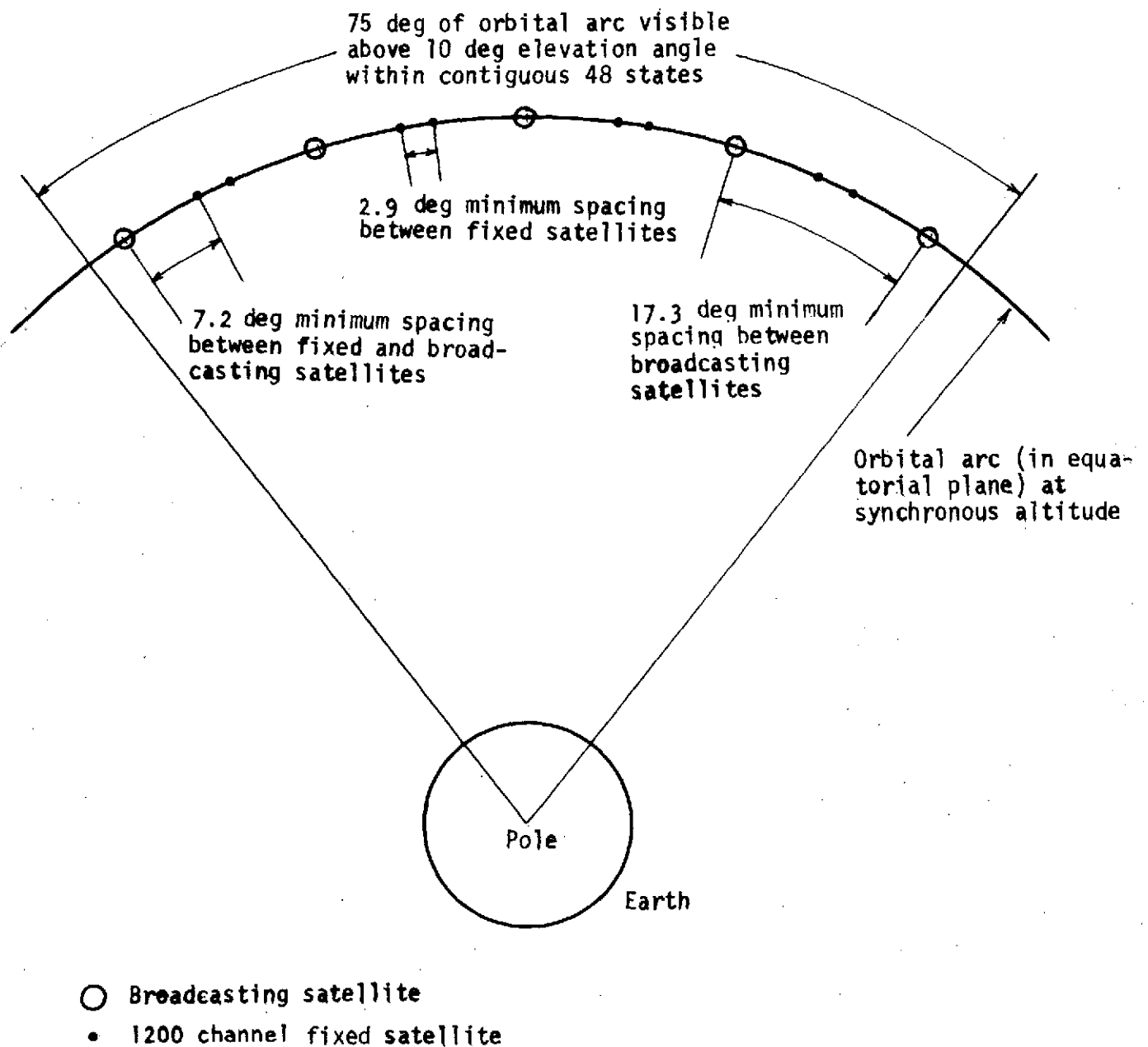


Fig. 33--Typical orbit-division strategy for Subcase 1b

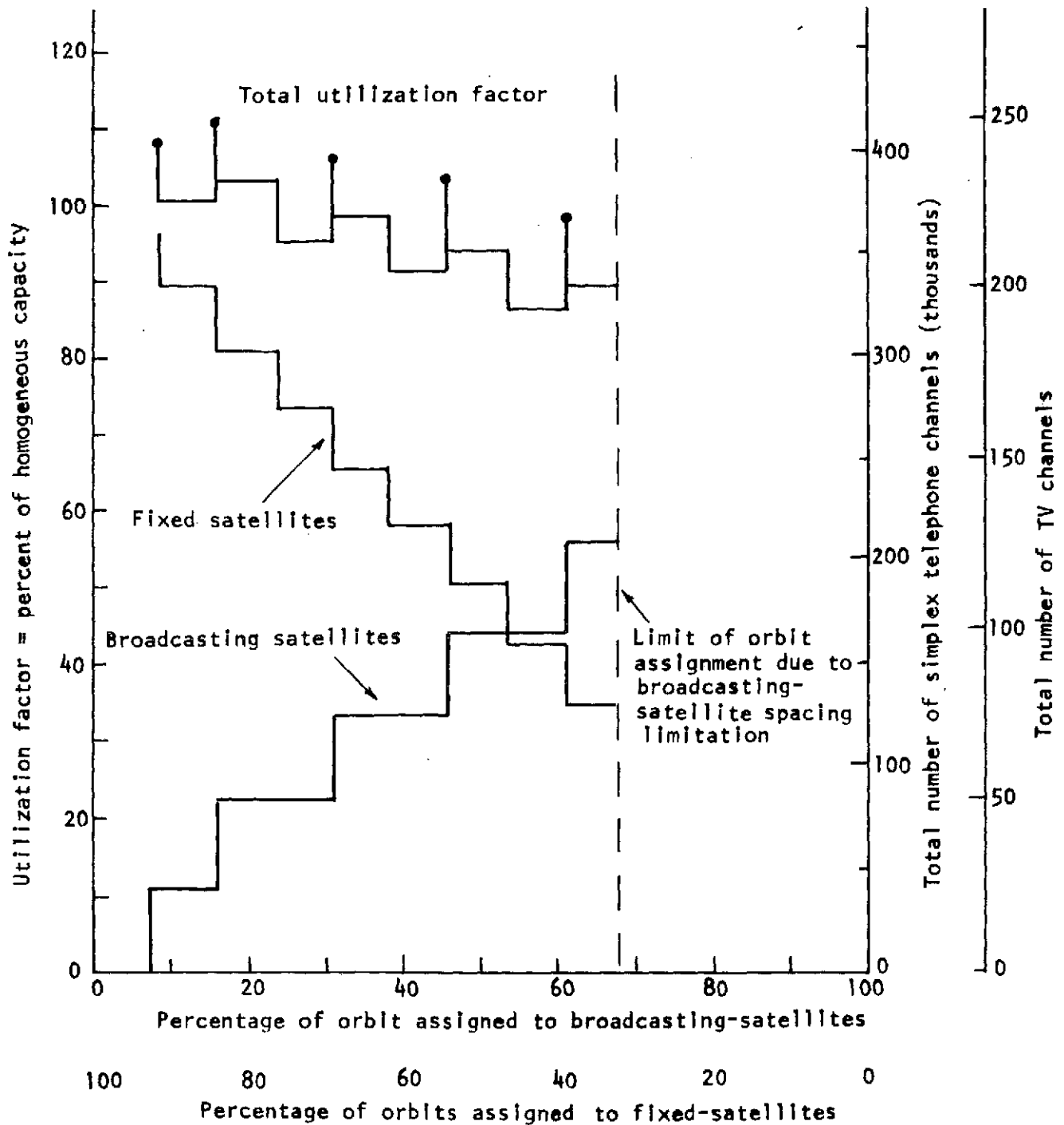


Fig. 34--Utilization factors for orbit division between 36 MHz 1200 channel, fixed-satellite links and 18 MHz, individual-reception, TV broadcasting-satellite links (Case 1b)

in spacing then reduces the number of broadcasting satellites, and hence their utilization factor, with no change in occupancy. The process may be continued in this fashion until only one broadcasting satellite is left. A similar effect occurs in the fixed-satellite service as fixed satellites drop out of the 75 deg arc, except that the step size is smaller than in the broadcasting case because of the larger initial number of fixed satellites.

It is seen that as with spectrum division, the total utilization factor is nearly 100 percent for all divisions of the orbit between the services. Unlike spectrum division, the total utilization factor does change slightly with the assigned shares, becoming gradually worse as the share assigned to the broadcasting-satellite service increases. A more significant difference from a theoretical point of view, although it is unlikely to be of practical importance, is that there is an upper limit of 67 percent to the share of the orbit that can be assigned to the broadcasting-satellite service.

Broadcasting Satellites Clustered at Ends of a Central Cluster of 1200 Channel Fixed Satellites (Subcase 1c). A special type of clustered deployment in which all of the fixed satellites are grouped in the center of the shared 75 deg of orbit, and the broadcasting satellites are clustered at the ends, might offer advantages in orbit-spectrum utilization over the deployment of a comparable number of satellites in a configuration of the type considered in Subcase 1b. To test this possibility, a sample deployment consisting of a cluster of 12 fixed satellites with clusters of 2 broadcasting satellites at each end was analyzed and the approximate spacings tested and refined using the computer simulation program. The preferred intersatellite spacings were found to be

$$\phi_{FF} = 3.1 \text{ deg}$$

$$\phi_{BF} = 5.6 \text{ deg}$$

$$\phi_{BB} = 11.4 \text{ deg}$$

Using these spacings, the number of fixed satellites in the central cluster can be expanded to a maximum of 14, while retaining two broadcasting satellites at each end of the allowed arc. The orbit share and utilization factor for the broadcasting-satellite service in this case are 42 percent and 44.4 percent, respectively. The corresponding fixed-satellite percentages are 58.4 percent and 53.8 percent, respectively. The total utilization factor is 98.2 percent. The deployment of Subcase 1b also permits 4 broadcasting satellites to share the orbit with 14 fixed satellites, so the utilization factors and number of channels provided are identical--only the percentage occupation is different: 45.9 percent for the broadcasting-satellite service, and 54.1 percent for the fixed-satellite service.

It is concluded that there is no special advantage to locating the broadcasting satellites at the end of the arc for the pair of baseline system and the fixed-satellite carrier size in question.

Other Subcases Considered (Subcases 1d-1i). With the background provided by the foregoing detailed discussion of Subcases 1a-1c, a summary description should suffice for the remaining subcases that were investigated for sharing between the baseline systems of Case 1.

The configurations and preferred intersatellite spacings derived by a combination of parametric analysis and computer simulation for the six other subcases considered are shown in Table 14 together with a recapitulation of the results for Subcases 1a-1c. The deployments of 1d and 1e are similar to those of 1b and 1c, respectively; the principal difference in the subcases being that the fixed-satellite links carry 900 channels, rather than 1200, and the intersatellite spacings are correspondingly smaller. Deployments 1f and 1g are both cluster deployments featuring groups of from 6 to 12 600 channel fixed satellites between adjacent broadcasting satellites. In particular, deployment 1g was intended to serve as a reference against which to compare the results of Subcases 1h and 1i.

These last two subcases were intended to test the extent to which orbit-spectrum utilization could be enhanced by means of sidelobe reduction techniques applied to the earth-station antennas of both fixed-satellite and broadcasting-satellite systems. Although the

Table 14

ORBIT-DIVISION SATELLITE DEPLOYMENTS AND COMPATIBLE
INTERSATELLITE SPACINGS FOR CASE 1 BASELINE SYSTEMS

Subcase ^a	Satellite Deployment	Compatible Intersatellite Spacings (deg)		
		ϕ_{FF}	ϕ_{BF}	ϕ_{BB}
1a	. o . o . o . o .	14.0	7.0	14.0
1b	.. o .. o .. o .. o ..	2.9	7.2	≥ 17.3
1c	o o o o	3.1	5.6	11.4
1d	o o o o	1.96	5.2	≥ 16.4
1e	o o o o	2.04	5.2	11.1
1f	....o.....o.....o.....o....	1.18	5.2	≥ 16.4
1g	.....o.....o.....o.....o.....	1.18	5.2	≥ 16.4
1h	Same as 1g but with 25 dB side-lobe reduction on earth-station antennas	1.05	3.8	≥ 16.4
1i	Same as 1g but with 40 dB side-lobe reduction on earth-station antennas	0.8	2.4	13.4

^aFixed-satellite links carry 1200 channels in Subcases 1a-1c, 900 channels in 1d and 1e, and 600 channels in 1f-1i.

CCIR has not adopted earth-station pattern envelopes incorporating sidelobe reduction, the CCIR patterns for broadcasting-satellite antennas serve nicely for this purpose. Thus, Case 1h assumed satellite pattern B-B (see Fig. 18) to represent the effect of "normal" sidelobe reduction techniques on the angular discrimination of earth-station antennas, and Case 1i adopted pattern B-C to represent the limit of the current state of the art in such techniques.

The results of the various subcases may be inferred from an inspection of the intersatellite spacing columns. Thus, reducing the number of fixed-satellite channels from 1200 to 900 permitted reductions in spacing for the orbit-division deployments comparable to those observed with exclusion occupancy or spectrum-division sharing. A further reduction from 900 to 600 channels had a similar effect, although

neither reduction in carrier size produced dramatic increases in orbit-spectrum capacity, and the utilization factors were affected very little. Probably the biggest improvement both in orbit-spectrum utilization and in utilization factors were observed with Subcases 1h and 1i.

Figure 35 is presented as an illustration of the utilization and capacities that could be achieved at the assumed 40 dB "limit" of sidelobe control (or with 25 dB of "normal" sidelobe control and an augmented interference objective of 2000 pWOp). Two features stand out in this subcase. First, the limit to the fraction of the orbit that can be assigned to broadcasting satellites has been reduced to 32 percent by the minimum spacing constraint in that service. But this feature is ameliorated and overshadowed by the second feature which is that the utilization factor for the broadcasting-satellite service significantly exceeds the fraction of the orbit assigned to it. Moreover, there is no corresponding penalty in the utilization factor of the fixed-satellite service. Specifically the broadcasting-satellite utilization factor is more than double that possible for the same share of the allocation with spectrum division, while the utilization by the fixed-satellite service is only a few percent less than with spectrum division.

This important result is reflected by the total utilization which, as shown in Fig. 35, can be as high as 135 percent. The conclusion is that, for sharing between fixed-satellite and broadcasting-satellite systems similar to those considered and where the demands for broadcasting channels can be met by less than a 32 percent share of the orbit-spectrum resource, orbit sharing is clearly preferable to spectrum sharing.

Sensitivity of Results to Various Sharing Tactics

All of the strategies just evaluated for sharing the orbit-spectrum resource between Case 1 baseline systems assumed that the links within a given service were co-channel and co-polarized. In most of the subcases, the 1000 pWOp CCIR objective for interference to a telephone channel was adopted for the fixed-satellite service and no allowance

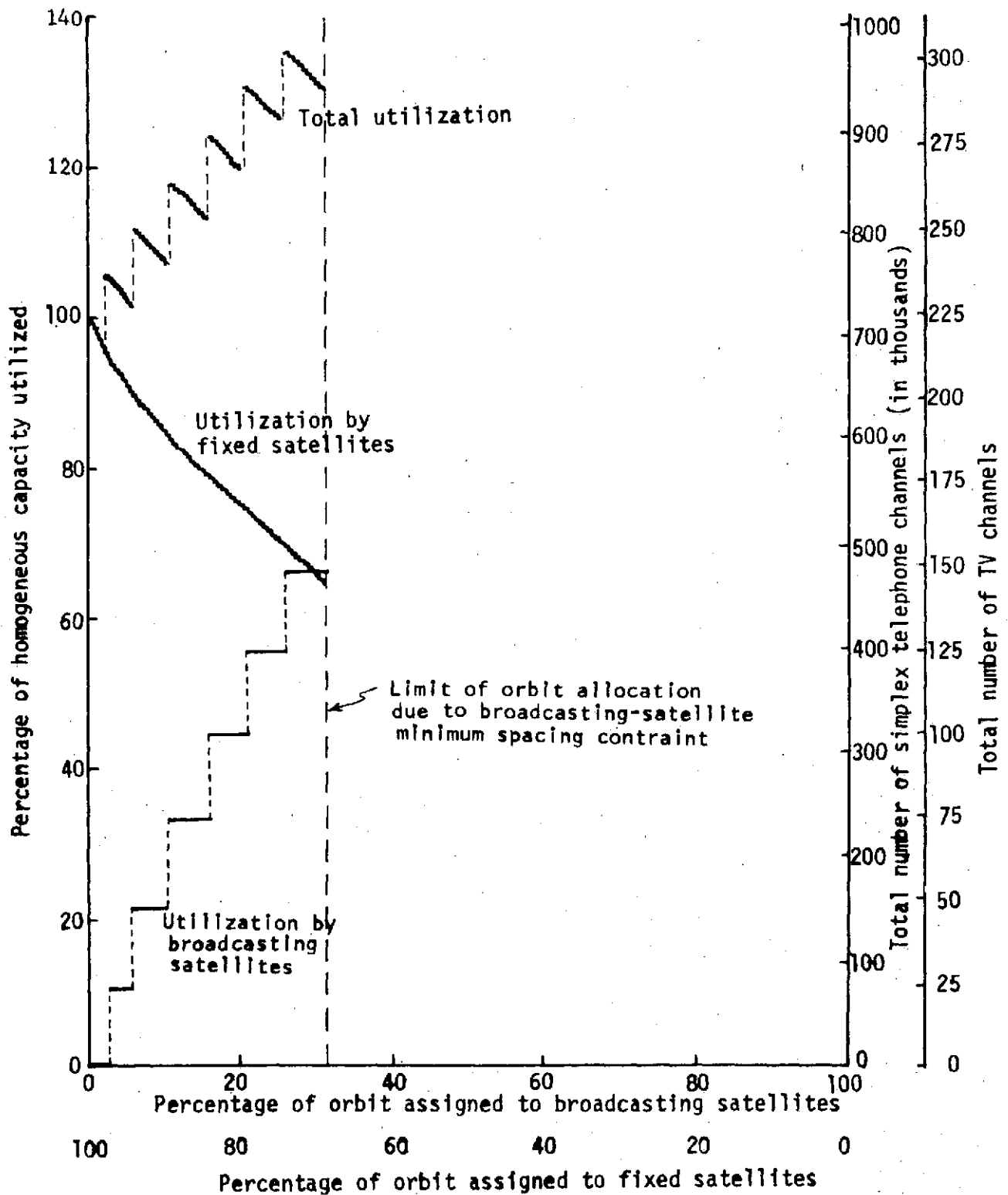


Fig. 35--Utilization factors for orbit division between 36 MHz, 600 channel, fixed-satellite links and 18 MHz, individual-reception, TV broadcasting-satellite links with sidelobe reduction on all earth-station antennas (Subcases 1h and 1i)

was made for the masking effects of noise in the case of the broadcasting-satellite service. Standard CCIR antenna pattern envelopes were used, and crossed-path geometry (see Sec. V) was not assumed for the broadcasting satellites.

On the other hand, the effect of varying the modulation index of the fixed-satellite links was investigated explicitly for all strategies and the conclusions in Sec. V regarding the impact of this sharing tactic were verified. The effects of changing interference objectives, antenna patterns, and path geometry were also evaluated for specific strategies. Again the results were in accord with the general analyses of Sec. V.

It remains to evaluate the impact of the various forms of frequency and polarization coordination discussed in Sec. V and diagrammed in Fig. 25. For this purpose, clustered satellite deployments similar to Subcase 1f were modeled using cross-polarization on the links to adjacent satellites, either by itself as described schematically in Fig. 25b, or in conjunction with frequency interleaving as in Fig. 25e. In both cases, the "worst-case" cross-polarized antenna patterns (10 dB sidelobe discrimination) were assumed, but care was taken to ensure that not only dissimilar adjacent satellites but adjacent satellites of the same kind were cross polarized even when separated by a cluster of unlike satellites (this implies clusters containing an even number of satellites).

The results were unequivocal. The computer simulations show that cross-polarized operation in all cases permitted intersatellite spacings to be reduced by at least half. And, when combined with frequency interleaving, the number of transponders and hence the capacity of each satellite could be doubled, with no penalty of increased interference. The evaluation was limited to single-carrier-per-transponder links. It is expected that cross-polarized operation would be equally as effective with multiple carrier operation, but the applicability of frequency interleaving to this type of operation remains to be investigated.

CASE 2: SHARING BETWEEN FIXED-SATELLITE SYSTEMS WITH LARGE TERMINALS
AND BROADCASTING-SATELLITE SYSTEMS FOR COMMUNITY RECEPTION

System Descriptions and Spectrum-Division Results

A summary listing of the principal parameters, message objectives, and frequency plans assumed for this case is given in Table 15. As in Case 1, carrier sizes of 600, 900, and 1200 channels were selected for use on the fixed-satellite links, and the analysis began with a determination of the spacings and capacities for exclusive occupancy of the orbit-spectrum resource by each of the baseline systems. The values for these quantities are displayed in Table 16.

Comparing the broadcasting-satellite system capacities in the two cases, it will be noted that the higher modulation index and larger earth-station antenna assumed for the community reception system enable it to have a homogeneous capacity over three times greater than that of the individual-reception system of Case 1, despite a 6 dB deficit in eirp. The principal cause of this higher orbit-spectrum utilization is the greater angular discrimination and hence smaller satellite separations permitted by the community-reception antenna.

Comparing the homogeneous spacing for the broadcasting satellites with those for the fixed satellites, it should be observed that the former is significantly smaller than the latter for 1200 channels and about 10 percent smaller for 900 channels. It is only for 600 channel fixed satellites that the popular notion that broadcasting-satellite spacings are larger than those for fixed satellites is borne out. Even here, the broadcasting-satellite spacing is only 37 percent greater.

A plot of the single service and total utilization factors for a spectrum-division strategy with the Case 2 baseline systems would look very much like Fig. 32 for Case 1, with two exceptions. First, the "step-size" for the broadcasting-satellite utilization factor curve would be 13 percent larger because of the wider bandwidth assumed for the community-reception TV/FM signal. Second, the television capacity scale at the right side of the graph would have to be renumbered to make 756 channels correspond to a utilization factor of 100 percent.

Table 15

PARAMETERS FOR CASE 2 BASELINE SYSTEMS

Quantity	Symbol	Unit	Broadcasting-Satellite System (BC)	Fixed-Satellite System (FL)
<u>Satellite Transmitter</u>				
Transmitter power	P	W	40	38
Antenna beamwidth	θ_o	deg	1.7 x 3.3	3.5 x 7
Antenna pattern ^a	-	-	B-B	F
eirp	E	dBW	52	46
<u>Earth Station Receiver</u>				
Receiving antenna diameter	D	ft	12	32
Antenna pattern ^b	-	-	C	F
System temperature	T	°K	500	250
Figure-of-merit	G/T	dBW/°K	24	35
<u>Signals</u>				
Carrier type	-	MHz	TV/FM	FDM/FM
Signal bandwidth	W	MHz	23	36
Channel spacing	-	MHz	26.7	40
Uplink carrier frequencies	-	GHz	14.013, 14.040	14.02
Downlink carrier frequencies	-	GHz	11.713, 11.740	11.72
<u>Message Objectives</u>				
Total thermal noise ^c	$\left(\frac{S}{N_w}\right)_o, N_o$	dB, pWOp	49	5000
Downlink thermal noise ^c	$\left(\frac{S}{N_w}\right)_{down}, N_{down}$	dB, pWOp	50	4000
Total interference ^c	ρ_o, I_o	dB, pWOp	24.7	1000
Downlink interference ^c	ρ_{down}, I_{down}	dB, pWOp	26.0	590

^aSee Fig. 18 for code.

^bSee Fig. 17 for code.

^cThe first entry in the symbol and unit columns applies to system BC, the second entry to System FL.

Table 16

SATELLITE SPACINGS AND ORBIT-SPECTRUM CAPACITIES
AND UTILIZATIONS FOR EXCLUSIVE OCCUPANCY BY
CASE 2 BASELINE SYSTEMS (see Table 15)

Quantity	Symbol	Unit	Broadcasting-Satellite System (BC)	Fixed-Satellite System (FL)		
Number of channels per carrier	n	-	1	600	900	1200
Modulation index	M,m	-	1.74	1.94	1.19	.813
Homogeneous spacing	ϕ_h	deg	1.8	1.14	2.0	3.0
Number of satellites ^a	-	-	42	67	38	26
Capacity per satellite ^a	-	Channels	18	7,200	10,800	14,400
Total capacity ^a	-	Channels	756	482,400	410,400	374,400
Orbit-spectrum utilization ^b	U	$\frac{\text{Channels}}{\text{MHz deg}}$	0.020	12.9	10.9	10.0

^aFor 75 deg of orbit and $12 \times 36 = 432$ MHz of spectrum.

^bThe values in this table will differ slightly from those calculated using Eqs. (121) and (122) because of rounding errors and because they were calculated using the discrete numbers of satellite shown in the table.

However, the utilization factors for each service would still be approximately equal to the share of the spectrum assigned to that service and there would be no intrinsic restrictions on the size of the share that could be assigned to either service. Also, as with the Case 1 systems, the effect of changing the number of channels on the fixed-satellite links could be accounted for by scale factors--the same factors that are shown in Fig. 32.

Orbit-Division Strategies

Orbit-division strategies for Case 2 were analyzed in the same manner as for Case 1. That is, approximate values of intersatellite spacings were first derived using the method described in Sec. V and illustrated in connection with Subcases 1a and 1b. Then, computer simulation was used where necessary to refine the approximate values. There are two principal differences from Case 1 to be taken into account in postulating orbital deployments, and in calculating compatible intersatellite spacings. The first is the previously noted fact that the homogeneous broadcasting-satellite spacings can be, and in two out of three of the subcases are, smaller than those of the fixed satellites. Second, the frequency plan is somewhat different, with three broadcasting channels occupying the same bandwidth as two of the fixed-satellite channels.

The three deployments analyzed for sharing with 1200 channel fixed-satellites were verified using the computer program. They are diagrammed and the resultant intersatellite spacings given in Table 17. Referring to this table, the first thing to note is the fact that the spacings required between like satellites are generally smaller than those required between unlike satellites, a property that was true only for the fixed-satellite service in Case 1. In particular, the fact that the spacing ϕ_{BB} is always less than ϕ_{FF} suggests that a clustered deployment like that shown for Subcase 2a is not a "natural" configuration and not likely to be an efficient one.

Basically, the reason is that, because of their lower protection ratios and higher eirps, the broadcasting-satellite links are quite

Table 17

ORBIT-DIVISION SATELLITE DEPLOYMENTS AND COMPATIBLE SPACINGS
FOR SHARING BETWEEN CASE 2 BASELINE SYSTEMS

(see Table 15)

Subcase	Satellite Deployment	Compatible Intersatellite Spacings (deg)		
		ϕ_{FF}	ϕ_{BF}	ϕ_{BB}
2a	o.....o.....o.....o	2.8	3.0	≥ 2.4
2b	.....oooo.....	2.9	4.0	2.1
2c	oo.....oo	3.0	4.0	1.9

insensitive to interference from fixed-satellite links. By the same token, the links to the fixed satellites are quite vulnerable; the larger value of ϕ_{BF} reflects the angular protection they require. In a configuration like Subcase 2a, the broadcasting satellites are much too far apart to interfere with each other, and the spacings needed to protect fixed satellites from them make interference from that source negligible as well. The result is that carrier-to-interference ratios in the broadcasting-satellite service areas will typically exceed the protection ratios by 12 dB or more. This situation reflects itself clearly in the utilization factor curves for this case shown in Fig. 36. Although the fixed-satellite utilization factor is slightly higher than the percentage of the orbit assigned to it, the broadcasting-satellite utilization is significantly less than its share of the orbit. As a result, the total utilization factor becomes progressively worse as the fraction of the orbit assigned to the broadcasting-satellite service increases. At the 50 percent point the cluster deployment becomes an alternating deployment and the utilization factor is down to 80 percent.

Subcases 2b and 2c represent different forms of cluster deployment in which the satellites of both services are clustered and the number of interfaces between clusters is reduced to two. An inspection of the intersatellite spacings shown in Table 17 suggests that

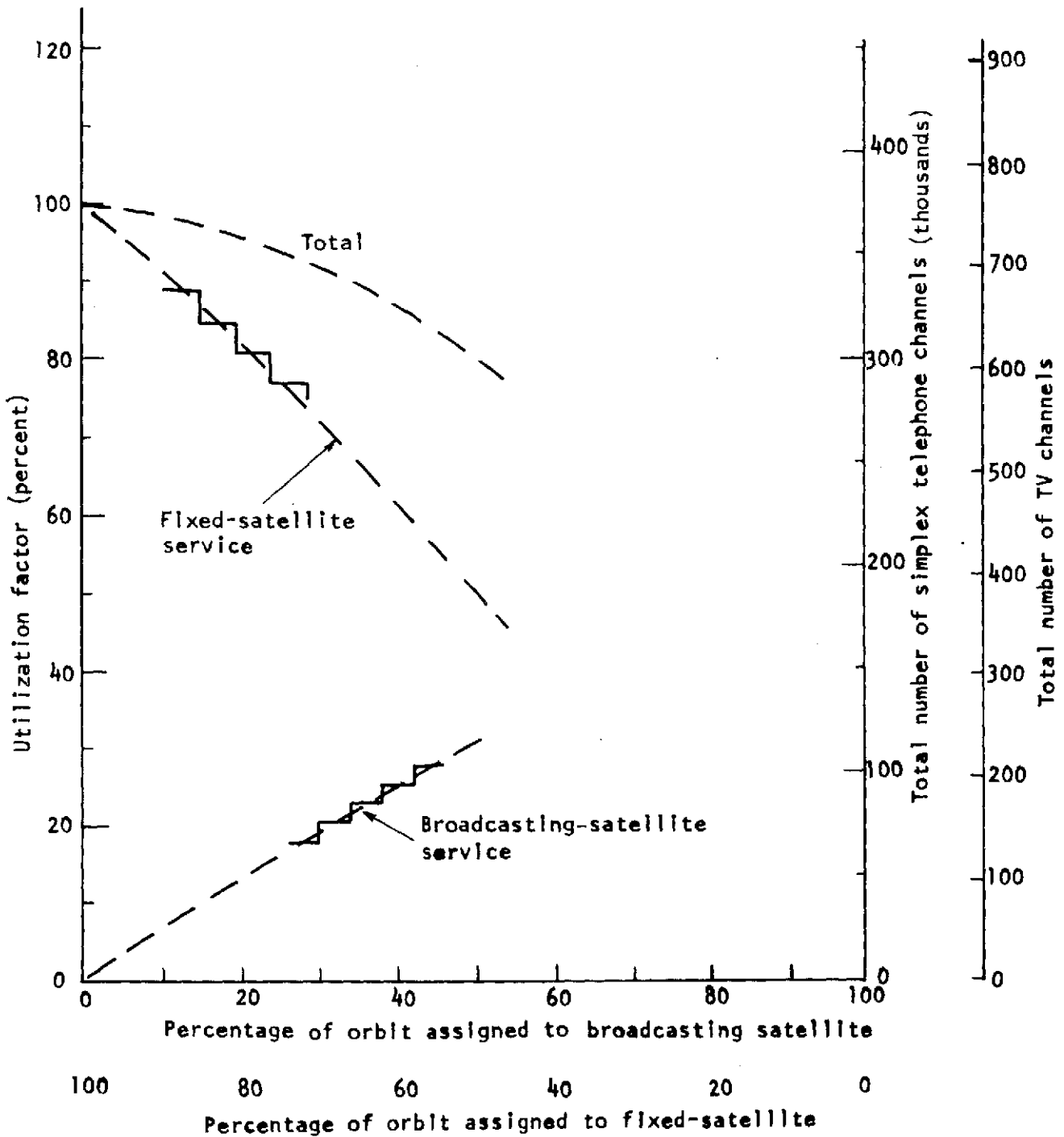


Fig. 36--Utilization factors for orbit division between 36 MHz, 1200 channel, fixed-satellite links and 23 MHz, community-reception, TV broadcasting-satellite links (Subcase 2a)

for the same number of satellites of each kind, these two strategies will yield virtually identical performance. Indeed, it is likely that the small differences between corresponding spacings computed in the two subcases are more a reflection of the different path geometries involved in providing service to the same assumed earth-station locations with different satellite locations than of any intrinsic difference between the efficiencies of the strategies. Comparing the spacings of Table 17 with the homogeneous spacings of Table 16 it is evident that total utilization will be close to 100 percent in both subcases.

No separate investigation of the sensitivity of the Case 2 strategies to the use of other sharing tactics was made because there is no reason to believe that the effects would be materially different from those described in connection with Case 1.

CASE 3: SHARING BETWEEN FIXED-SATELLITE SYSTEMS WITH SMALL TERMINALS AND BROADCASTING-SATELLITE SYSTEMS FOR COMMUNITY RECEPTION

At this point, the general principles of analyzing sharing strategies should be fairly evident so that less detailed descriptions of the subcases and discussions of results will suffice. For example, the systems may be described by referring to Table 15 and merely noting that the broadcasting-satellite system for Case 3 is identical to the one described there and the fixed-satellite system differs from its Case 2 counterpart only in the diameter of the earth-station antenna (16 rather than 32 ft), and the associated figure-of-merit (29 rather than 35 dBW/°K). Likewise, the homogeneous spacings, capacities, and utilizations can be shown in the same table with the satellite deployment diagrams and intersatellite spacing results, as has been done in Table 18.

From a comparison of the intersatellite spacings, it would appear that both deployments 3a and 3c offer excellent orbit-spectrum utilization with total utilization factors in the order of 105 percent. The deployment of Subcase 3b is the least efficient for some of the same reasons that made a cluster deployment of this type less than optimum with the systems of Case 2. Thus, the broadcasting satellites exhibit

Table 18

RESULTS FOR EXCLUSIVE OCCUPANCY AND ORBIT-DIVISION
FOR CASE 3 BASELINE SYSTEMS

a. Spacings, Capacities, and Utilizations for Exclusive Occupancy				
Quantity	Symbol	Unit	Broadcasting-Satellite System (BC)	Fixed-Satellite System (FS)
Number of channels per carrier	n	-	1	600
Modulation index	M _m	-	1.74	1.94
Homogeneous spacing	ϕ_h	deg	1.8	2.0
No. of satellites	-	-	42	38
Capacity per satellite	-	Channels	18	7200
Total capacity	-	Channels	756	273,600
Orbit-spectrum utilization	U	$\frac{\text{Channels}}{\text{MHz deg}}$	0.020	7.3

b. Orbit-Division Satellite Deployments and Spacings				
Subcase	Satellite Deployment	Compatible Intersatellite Spacings (deg)		
		ϕ_{FF}	ϕ_{BF}	ϕ_{BB}
3a	.o.o.o.o.o.o.	3.6	1.8	3.6
3b	o.....o.....o.....o	2.2	2.4	≥ 1.0
3c	oo.....oo	2.0	2.0	1.9

unnecessarily high carrier-to-interference ratios because they are too far apart to interfere with each other, but cannot be brought closer to the fixed satellites without causing excessive interference to them. All things considered, deployment 3c would appear the best compromise between utilization and flexibility. An equally efficient strategy, not tested for Case 3, would centralize the broadcasting-satellite cluster as in the deployment of Subcase 2b.

Application of the various sharing tactics discussed in Sec. V should provide the same scaling factors for enhancing orbit-spectrum utilization as indicated in that section and verified in the analysis of Case 1.

VII. CONCLUSIONS AND RECOMMENDATIONS

GENERAL CONCLUSIONS

Feasibility of Interservice Sharing

The most general conclusion to be drawn from this study is that the band from 11.7 GHz to 12.2 GHz can in fact be shared effectively by broadcasting-satellite and fixed-satellite systems. That is, with proper coordination in the positioning of satellites, in the arrangement of rf channels, and in the polarization of antennas, the utilization of the orbit and spectrum can equal or exceed that possible with an exclusive allocation to one or the other service.

This conclusion can be stated more precisely in terms of the concept of orbit-spectrum "utilization factor." The utilization factor for a service that shares the orbit-spectrum resource is defined as the ratio of the capacity that systems in the service can provide when using an assigned share of the resource to the capacity they could provide if given exclusive use of the entire resource. The total or joint utilization factor, defined as the sum of the utilization factors for the individual services, then provides an unambiguous, dimensionless, figure-of-merit for expressing the effectiveness of a sharing strategy. The higher the total utilization factor, the more effective the strategy. In these terms, the basic conclusion is that, for any specified combination of systems representing the two services and for any assigned division of the orbit-spectrum resource between them, a sharing strategy can be found that permits the total utilization factor to approach or even to exceed 100 percent.

The choice of a preferred strategy depends critically on the signal and equipment parameters of the systems in the two services and on the relative size of the orbit-spectrum shares assigned to them. The system parameters depend, in turn, on the nature, diversity, and absolute magnitudes of the communication needs in each service, since these determine the kinds and numbers of systems that must be built and hence the degree of intersystem inhomogeneities that must be

accommodated by the sharing strategy and the intensity with which the orbit-spectrum resource must be utilized. The relative size of the assigned shares will presumably be determined by the relative magnitudes of the service needs.

Preferred Type of Strategy

A comparison of the two fundamental categories of sharing strategies, spectrum division and orbit division, leads to the following conclusions. A spectrum-division strategy, in which each service can occupy the entire visible orbital arc but is assigned only a part of the 500 MHz frequency band, has several useful features. It imposes no restrictions on the relative size of the share of the orbit-spectrum resource assigned to each service and, regardless of the nature of the systems in the services or their lack of homogeneity, the utilization factor for each service will be very nearly equal to the size of the assigned share. That is, relative to the capacity it could provide with an exclusive allocation, each service can provide a capacity about equal to the fraction of the resource assigned to it. As a result, the total utilization factor with spectrum sharing is always close to (but cannot exceed) 100 percent.

Spectrum sharing also imposes a serious constraint. Since each satellite can use only a fraction of the total spectrum, a larger number of satellites are required to provide a given total communication capacity. This would not be a serious restriction if the cost of a satellite, including launch, was directly proportional to its communication capacity. But this is far from the case in practice, and the need for additional satellites and for the additional earth-station capability that might be required to work with them, must be counted as a major liability for spectrum division.

An orbit-division strategy on the other hand, permits all satellites to use the entire spectral band but restricts their freedom of orbital location. Particular care must be exercised in the choice of locations for the different satellites and in the angular separations maintained between adjacent satellites. With the aid of methods for

calculating spacings like those developed in Sec. V and applied to representative mixes of systems in Sec. VI, an effective orbit-sharing strategy can always be found. That is to say, an orbital deployment for the satellites of the two services can be found which yields a total utilization factor approaching or even exceeding 100 percent.

The latter possibility simply reflects the fact that orbit-sharing can permit one service to have a utilization factor significantly higher than its assigned share of the orbit while that of the other service remains about equal to its assigned share. Such a situation usually involves an upper limit on the fraction of the orbit that can be assigned to the service with the high utilization factor, but this is not a serious restriction precisely because the utilization factor is high--i.e., the service is already delivering a significant fraction of the capacity it could provide with an exclusive allocation.

The careful interservice coordination of satellite positions required by an orbit-division sharing strategy cannot be discounted in comparing it with a spectrum-division strategy. In point of fact, though, the problem differs only in degree from the intraservice coordination of satellite positions intrinsic to both kinds of strategies. Considering that orbit-division offers comparable or, in some cases, superior orbit-spectrum utilization, with fewer economic and operational penalties and not substantially more difficult system coordination problems, it is concluded that a properly chosen orbit-division sharing strategy is to be preferred over a spectrum-division strategy. Guidelines for choosing a particular orbit-sharing strategy to match specified types of systems and total service requirements will be discussed later in this section.

Sharing Among Nations

The orbit-spectrum resource is to be shared not only between services but also among the domestic systems of all of the nations in ITU Region 2 (the Americas). The problem of international sharing is made tractable by the large total communication capacity available at 12 GHz, the interference-reducing effect of the spot-beam satellite antennas implied by the restriction to domestic systems, and the fact that the

usable segments of geostationary orbit are spread over a wide range in longitude. It is tentatively concluded that, except for Canada, the probable demands of other Region 2 countries for fixed- and broadcast-satellite systems can be met without special coordination with U.S. systems by using segments of the orbital arc not usable by the United States and Canada. However, as in the case of domestic fixed-satellite systems in the 4 GHz band, U.S. sharing strategies for the 12 GHz band should be chosen in close consultation with Canadian regulatory agencies.

SATELLITE DEPLOYMENTS AND CAPACITIES FOR BASIC ORBIT-DIVISION STRATEGIES

The most fundamental property of an orbit-division strategy is the satellite deployment plan that it employs, including the intersatellite spacings that must be maintained. The sharing tactics embodied in the strategy, like frequency-interleaving and crossed-polarized operation, normally serve only to reduce all of the required spacings by the same factor. While this increases the total available communication capacity and so enhances the orbit-spectrum utilization, it has little effect on the utilization factor. In this sense, the selection of the preferred orbit-division strategy reduces to an identification of the preferred orbital deployment.

The choice of satellite deployment depends in turn very strongly on the parameters of the systems which are to share the orbit and on the characteristics of the signals they carry. Considerable insight into this dependence can be gained from a consideration of the preferred deployments for representative combinations of systems representing the two services.

The Basic Strategy in a Family of Orbit-Division Strategies

The specific conclusions about preferred deployments that follow are based on the cases analyzed in Sec. VI. The intersatellite spacings and orbit-spectrum capacities to be cited assume an orbit-division strategy in which satellite paths are not crossed, all the links in a given service are both co-polarized and co-channel, the interference objective for telephone channels is 1000 pWop and the protection ratio for

television channels does not allow for interference masking by noise. These assumptions define the "basic strategy" in the family of orbit-division strategies that have the same preferred satellite deployment (as determined by the assumed mix of baseline systems) but employ different combinations of sharing tactics.

Fixed-Satellite Systems and Individual-Reception Broadcasting-Satellite Systems

Consider first the case of sharing between fixed-satellite systems using 46 dBW satellites with 32 ft earth stations and broadcasting-satellite systems using 58 dBW satellites with 3 ft receiving antennas for individual reception. The preferred orbit-division strategy employs a clustered deployment in which at least two fixed satellites are placed between adjacent broadcasting satellites. This strategy yields about 220,000 telephone channels and 100 television channels when 47 percent of the resource is assigned to the broadcasting-satellite service. For a 20 percent assignment, the service capacities are about 300,000 telephone channels and 50 TV channels.

These numbers assume that the fixed satellites are used for 1200 channel links. The spacing of about 3 deg between adjacent fixed satellites will permit these satellites to be operated with any smaller number of channels either on a single- or multiple-carrier-per-transponder basis, but the total capacity with such operation will be reduced in proportion. For example, with multiple carriers, the capacity of a transponder will be in the order of 600 to 700 telephone channels rather than 1200 to 1500 channels. If carrier levels and modulation indices are chosen for minimum-power operation as described in Sec. VI, interference will not be objectionable with any combination of carrier sizes or frequency plans.

If the maximum capacity of the fixed-satellite links is reduced to 900 channels, the cluster-deployment becomes even more effective and the spacings between fixed satellites in a cluster can be reduced to about 2 deg with an increase of about 12 percent in the total channel capacity available from such satellites. Compatible multiple-carrier-per-transponder operation will still be guaranteed with

properly chosen carrier parameters, and the aggregate capacity for such operation will still be in the order of 600 to 700 channels per transponder.

A further reduction in the maximum size of fixed-satellite carriers to 600 channels permits still further spacing reductions and capacity increases, but now the sizes, power levels, and frequencies of carriers in multicarrier operation have to be very carefully controlled to achieve interference compatibility. The preferred cluster strategy yields slightly higher utilization factors and total capacities, but fixed-satellite links with capacities greater than 600 channels cannot be operated at the reduced spacings.

Satellite deployments in which broadcasting satellites are themselves clustered at the ends of the visible orbital arc with all fixed satellites in a central cluster were found to be less effective than the deployments just described for all fixed-satellite link capacities below 1200 channels. At 1200 channels, the utilization factors were nearly equal for the two deployments.

Fixed-Satellite Systems and Community-Reception Broadcasting-Satellite Systems

If the individual-reception, broadcasting-satellite systems in the preceding case are replaced by ones designed for community reception using 52 dBW satellites with 12 ft receiving antennas, then clustering the fixed satellites between adjacent broadcasting satellites is no longer the most effective way to share the orbit. For example, with 1200 channel links and clustered satellites, fixed-satellite systems would require a 60 percent share of the orbit to offer the same capacity as before (220,000 channels), and although the broadcasting-satellite capacity from the remaining 40 percent of the orbit would be doubled to 200 television channels, the total utilization factor would only be 80 percent.

The effect of reducing the number of channels on the fixed-satellite systems in this case would be to decrease the spacings and increase the capacity of those systems in about the same proportions as before, with attendant improvements in the utilization factor. However, the

preferred orbit-division strategy is one in which satellites of both types are clustered. A utilization factor of nearly 100 percent can be achieved by grouping all satellites of one kind together and minimizing the number of interfaces between dissimilar satellites. Symmetrical deployments of this type include grouping either the broadcasting satellites or fixed satellites in a central cluster with half of the satellites of the other service clustered at each end of the visible orbital segment.

Fixed-Satellite Systems with Small Terminals and Community-Reception Broadcasting-Satellite Systems

When the community-reception system just considered shares the orbit with a fixed-satellite system employing a 46 dBW satellite with 16 ft earth stations, the smaller earth-station figure-of-merit reduces the maximum link capacity to 600 channels. The spacings required between dissimilar satellites become very nearly equal to those required between similar satellites (about 2 deg).

The satellite deployment for the preferred orbit-division strategy is the same as in the preceding case, although here, an alternating deployment (one in which alternate satellites are of the same kind) also yields a utilization factor of nearly 100 percent. In all of the preferred deployments for this case, the utilization factor for each service is closely equal to its assigned share of the orbit. The capacities for exclusive occupancy are 274,000 simplex telephone channels for the fixed-satellite service and 756 television channels for the broadcasting-satellite service. Thus, the fixed-satellite service would require a 73 percent share of the orbit to yield 200,000 channels, in which case the 27 percent broadcasting-satellite share would yield 204 channels.

Arbitrary Combinations of Systems

Several generalizations may be ventured on the basis of the foregoing results. When the inhomogeneities between different systems are large, the satellite deployment for the preferred orbit-division strategy features clusters of the satellites having the smaller homogeneous

spacing between adjacent pairs of the satellites with the larger homogeneous spacing. When there is moderate inhomogeneity, the preferred deployment will put each type of satellite in a separate cluster, minimizing the number of interfaces between dissimilar satellites. When the systems are essentially homogeneous, satellites may be equally spaced in any sequence at their common homogeneous spacing. In judging the degree of inhomogeneity, it should be noted that not only satellite eirp and earth-station diameter but also the interference objectives and signal parameters like modulation index must be considered. In choosing the spacing between similar satellites in a cluster, however, values nearly equal to the homogeneous spacing can normally be used.

The same principles for choosing intersatellite spacings apply to systems within a single service when that service involves systems with dissimilar characteristics--for example, the broadcasting-satellite service with systems for both community reception and individual reception. Moreover, in such cases, the principles can be applied independently in different parts of the orbit by virtue of the fact that most of the interference to a given satellite link comes from the links of the nearest satellites that operate on the same rf channel and with the same polarization.

It is seen that in all of the base cases just described, a total capacity of at least 200,000 simplex telephone channels is available from the fixed-satellite service using the preferred satellite deployment and an appropriate share of the orbit. For these orbital divisions, at least 100 channels were available from the broadcasting service when used for individual reception and at least 200 channels when used for community reception. Although optimum satellite deployments have not been derived and checked by computer simulation, it seems reasonable to conclude from the foregoing results that comparable total capacities could be provided by each service when all four of the baseline systems are deployed.

SHARING TACTICS

It has been noted that the effect of augmenting a basic sharing strategy through the addition of tactics such as cross-polarization,

carrier-frequency offsets, and crossed paths (see Sec. V), is usually to permit reductions in intersatellite spacings and corresponding increases in system capacities relative to those just cited for the basic orbit-division strategies. The magnitude of these effects will now be summarized.

If alternate polarization is used on all adjacent satellites in the deployment, spacings can be cut in half and the total capacities doubled. For example, the approximate 2 deg spacing between adjacent fixed satellites when used either for 900 channel links between 32 ft earth stations, or for 600 channel links between 16 ft earth stations, could be reduced to 1 deg. If carrier-frequency interleaving is used in addition to cross-polarization, the spacings remain the same but the capacity of each satellite will be doubled and the total capacity compared with the base case quadrupled.

Since there is little likelihood of interference from terrestrial systems in the 11.7 to 12.2 GHz band in the United States, the interference objective for fixed-satellite links could be doubled to 2000 pWOp with an accompanying 24 percent decrease in spacing and increase in capacity for this service. If the protection ratio for individual reception is lowered by 6 dB to account for the masking of interference by noise at the assumed 43 dB output signal-to-weighted noise level, spacings between broadcasting satellites could be reduced and the number of channels for that service would be more than doubled.

If the positions of broadcasting satellites with overlapping service areas are arranged to yield crossed-path operation as described in Sec. V, the spacings of those satellites can be reduced by about 30 percent with a corresponding increase in total channel capacity. It should be noted, however, that with this tactic, it is not usually possible to locate all satellites to the west of their respective service areas in order to postpone eclipse periods until after local midnight.

Finally, the use of sidelobe reduction techniques on earth-station antennas can yield further spacing reductions and capacity increases if the sidelobe suppression is greater than the single entry protection ratio for interference from adjacent satellites, after proper

allowance has been made for differences in eirp, frequency offset, and satellite antenna directivity. In a computer simulation involving fixed satellites with 32 ft antennas and individual broadcasting satellites with 3 ft antennas, the change was about 30 percent.

SUGGESTIONS FOR FUTURE WORK

Although the methods and conclusions developed in this study provide a sound technical approach to drawing up specific plans for sharing the orbit-spectrum resource between 12 GHz domestic fixed-satellite and broadcasting-satellite systems, it is considered premature to prepare such plans at this time. A detailed sharing plan should be based on better knowledge than is currently available in a number of areas. The following technical and economic studies and analyses are suggested as prerequisites for putting the conclusions of the present study on a more secure footing and extending its methods to a broader range of possible system designs so that detailed sharing plans can be prepared.

1. As described in Sec. IV, new or improved subjective measurements of interference protection ratios are needed both for combinations of the FDM/FM and TV/FM signals considered there and for interference between these signals and the digitally modulated telephone and television carriers likely to be used on future systems. The TV/FM signals should specifically include those using bandwidths narrower than the Carson's-rule bandwidth.

2. New 12 GHz propagation data and a more careful extrapolation of existing data on rain attenuation for higher frequencies are needed to be sure that the assumed fading allowances are neither too large nor too small.

3. Better data are needed on the overall polarization discrimination that might be achieved on interference paths involving the sidelobe regions of practical antennas.

4. A measurement program should be undertaken to determine the sidelobe performance actually achievable with antennas designed for individual reception to see if, and under what conditions, the present CCIR pattern envelope for this type of reception can be replaced by

one which would yield better orbit-spectrum utilization. Particular attention should be paid to the effects of inexpensive techniques for sidelobe reduction.

5. A joint study program between CCIR Study Groups 4 and 11 should be initiated with the object of reducing the profusion of different sidelobe envelope patterns (see Figs. 17 and 18) recommended by the CCIR for interference calculations. The present differences in such patterns can lead to conclusions regarding satellite spacing requirements for the two services that have no basis in engineering reality.

6. A study should be undertaken to determine the optimum bandwidths for the carriers of broadcasting-satellite and fixed-satellite systems with the object of aligning frequency plans in the two services so as to minimize interservice interference. Such a study would include an examination of noise and interference objectives for television reception in the broadcasting-satellite service and for telephone and television transmission in the fixed-satellite service. The former would take into account the protection ratio measurement programs described in Item 1, and the latter would consider the desirability of doubling the interference objective in regions where no terrestrial interference is expected. The study would also take account of better data on fading margins from the study suggested under Item 2, and should take a more careful look at the rules suggested in Sec. VI for choosing the sizes and power levels of FDM/FM carriers in the fixed-satellite service.

7. A market analysis of the growth in potential future demand for 12 GHz systems in both the fixed-satellite and the broadcasting-satellite services is needed to determine how to divide the usable orbit between these services and how intensely this portion of the orbit and spectrum resource will have to be utilized in the future.

8. The 12 GHz sharing study should be extended to assess the impact of new technological developments such as digital encoding and transmission of television, the use of adaptive array antennas for nulling out principal sources of interference, and other means for controlling both the shape of the main beam and the sidelobe levels.

The extension should include the relevant parametric analyses and modification of the computer program so that it may be used to verify the interference compatibility of sharing configurations appropriate to digital signals and shaped satellite antenna beams. The feasibility of a single general orbit-division strategy, applicable in stages to systems of both services as the need for more intense sharing increases, should be investigated.

9. The 12 GHz sharing study should also be extended to take an explicit look at sharing with other countries within ITU Region 2 and particularly those administrations who are actively planning system developments in this band. A primary object of this study would be to provide a firm technical basis for formulating a U.S. position for the 1977 ITU planning conference. Thus the study would also have to include consideration of possible sharing problems with the systems in ITU Regions 1 and 3.

10. A detailed orbit-spectrum sharing study should be carried out for the 2500 to 2690 MHz band which features not only sharing between fixed-satellite and broadcasting-satellite systems, but terrestrial systems as well. Only slight modifications to the computer simulation program would have to be made to adapt it for application to this frequency band.

Appendix

A COMPUTER PROGRAM FOR SATELLITE LINK INTERFERENCE PREDICTIONS

INTRODUCTION

When a number of communication systems have to share the same frequency band, mutual interference is inevitable, and careful system planning and coordination are required to keep the interference levels to acceptably low values. Parametric analysis of idealized system models can provide useful guidelines for preliminary system planning and for the selection of promising sharing strategies. However, for an accurate evaluation of a particular strategy as it might be applied to a mix of real systems, one must calculate the expected interference levels on a representative number of communication links using detailed system models. The calculations in question are quite straightforward but extremely tedious, especially when the number of links to be examined is large.

The reason for this is apparent from the equation expressing total interference on a link. If the number of links sharing a given rf channel is N , the interference level for the i th link is proportional to the weighted sum of the reciprocal carrier-to-interference ratios C_i/X_{ij}

$$\sum_{j=1}^N \left\{ \frac{1}{Q_{ij}} \left[\left(\frac{C_i}{X_{ij}} \right)_{\text{up}}^{-1} + \left(\frac{C_i}{X_{ij}} \right)_{\text{down}}^{-1} \right] \right\}, \quad i = 1, 2 \dots N$$

where Q_{ij} is the weighting factor and the sum is carried out over both the uplinks and downlinks of all $N-1$ interfering links.* The tedium arises not only because of the large number of terms to be computed $[2N(N-1)]$ but because each term involves the computation of many subsidiary quantities. Thus the weighting factor Q_{ij} depends on a number

* See Sec. IV for a detailed treatment of this problem.

of parameters of both the carrier and the interfering signal, and the carrier-to-interference ratios C_i/X_{ij} depend on a number of equipment and geometrical parameters of the wanted and unwanted systems.

To facilitate system planning and the evaluation of sharing strategies for the fixed-satellite and broadcasting-satellite services, Rand has developed a comprehensive new computer program for predicting interference levels. The general features of this program, a complete program listing, and a detailed description of its routines are given in the sections that follow.

GENERAL FEATURES

Performance

The program consists of one main routine and three subroutines recorded on about 650 IBM cards--less than half of a standard IBM box. (A complete listing is given at the end of this Appendix.) Despite its modest size, the program can easily handle quite large numbers of systems. Moreover, it does so with a comparatively small requirement for core storage. For example, to compute the interference among 120 links involving 50 satellites and 35 earth stations required only 86 kilobytes of core. The program is also reasonably fast; nine separate cases (different satellite configurations and/or system parameters) of the size just mentioned required about 72 seconds of machine time or about 8 seconds per case.

The program is written in Fortran IV, and, since it does not use a name-list or other esoteric options, it can be run on virtually any machine that reads this programming language. Construction of the program follows a "bread-and-butter" approach so that no special sophistication on the part of the programmer is required to modify the equations it incorporates or to extend it to include new options.

All input data are entered via punched cards using three standard Fortran formats. The required number of input data cards equals the number of links to be examined plus about 20. Total turnaround time for an entirely new problem from start of keypunching to delivery of printout typically runs about three hours.

Inputs

Complete lists of all program inputs will be given in the next section. Basically these inputs provide a detailed description of each of the fixed- and broadcasting-satellite systems and of the communications links that they provide. The system descriptions include the locations of all space stations and earth stations, and the points at which the transmitting and receiving antennas at these stations are pointed. For each station, the description includes the transmitter power, the dimensions, efficiency, and co- and cross-polarized envelopes of the transmitting and receiving antennas, and the receiving system noise temperatures. The description of each link includes the identity of the satellite and two earth stations involved, the uplink and downlink carrier frequencies, rf bandwidth, and the number and type of message channels.

Outputs

The normal or summary printout includes a detailed description of the system parameters and link geometry and a link-by-link breakdown of noise and interference levels, including the uplink and downlink contributions as well as the total. For fixed-satellite systems, the interference is expressed directly in picowatts at a point of zero relative level. For broadcasting satellites, the carrier-to-interference ratio is tabulated after weighting by the sensitivity factor Q . An example of a summary printout of system characteristics is given in Table A-1a. An example of a summary printout of noise and interference levels is given in Table A-1b.

If a more detailed look at the interference contributions is desired for diagnostic analysis--e.g., to determine the source of unusually high interference entries--a link-by-link listing of all $2N(N-1)$ interference entries can be commanded. In this printout, the individual interference contributions for each link are tabulated in the sequence that the links have been numbered. In addition to the individual contributions, the tabulation includes a description of the link geometry, the wanted signal power C_i , the unwanted signal power X_{ij} , the RTC or the sensitivity factor Q_{ij} , the antenna gain product

Table A-1a

EXAMPLE OF SUMMARY PRINTOUTS:
A. SYSTEM DESCRIPTION

4/24/74 CASE 2B 12", 1CH, 27MHZ BSC VS 32", 1200CH, 40MHZ FSH; SAT SEP=3,2.5,4.8

		G.S.DIA.	SAT.DIA.1	SAT.DIA.2	FREQUENCY	BANDWIDTH	EFFICIENCY	POWER	# CHANNELS	TEMPERATURE	POL.	G-PAT-
1	UP	32.000	1.440	0.720	14.020	36.000	0.550	1000.	1200.	1200.	0	3
	DOWN	32.000	1.720	0.860	11.720	36.000	0.500	40.	1200.	250.	1	3
2	UP	32.000	1.440	0.720	14.020	36.000	0.550	1000.	1200.	1200.	0	3
	DOWN	32.000	1.720	0.860	11.720	36.000	0.500	40.	1200.	250.	1	3
3	UP	32.000	1.440	0.720	14.020	36.000	0.550	1000.	1200.	1200.	0	3
	DOWN	32.000	1.720	0.860	11.720	36.000	0.500	40.	1200.	250.	1	3
4	UP	32.000	1.440	0.720	14.020	36.000	0.550	1000.	1200.	1200.	0	3
	DOWN	32.000	1.720	0.860	11.720	36.000	0.500	40.	1200.	250.	1	3
5	UP	32.000	1.440	0.720	14.020	36.000	0.550	1000.	1200.	1200.	0	3
	DOWN	32.000	1.720	0.860	11.720	36.000	0.500	40.	1200.	250.	1	3
6	UP	32.000	1.440	0.720	14.020	36.000	0.550	1000.	1200.	1200.	0	3
	DOWN	32.000	1.720	0.860	11.720	36.000	0.500	40.	1200.	250.	1	3
7	UP	32.000	1.440	0.720	14.020	36.000	0.550	1000.	1200.	1200.	0	3
	DOWN	32.000	1.720	0.860	11.720	36.000	0.500	40.	1200.	250.	1	3
8	UP	32.000	1.440	0.720	14.020	36.000	0.550	1000.	1200.	1200.	0	3
	DOWN	32.000	1.720	0.860	11.720	36.000	0.500	40.	1200.	250.	1	3
9	UP	32.000	1.440	0.720	14.020	36.000	0.550	1000.	1200.	1200.	0	3
	DOWN	32.000	1.720	0.860	11.720	36.000	0.500	40.	1200.	250.	1	3
10	UP	32.000	1.440	0.720	14.020	36.000	0.550	1000.	1200.	1200.	0	3
	DOWN	32.000	1.720	0.860	11.720	36.000	0.500	40.	1200.	250.	1	3
11	UP	32.000	1.440	0.720	14.020	36.000	0.550	1000.	1200.	1200.	0	3
	DOWN	32.000	1.720	0.860	11.720	36.000	0.500	40.	1200.	250.	1	3
12	UP	32.000	1.440	0.720	14.020	36.000	0.550	1000.	1200.	1200.	0	3
	DOWN	32.000	1.720	0.860	11.720	36.000	0.500	40.	1200.	250.	1	3
13	UP	16.000	1.440	0.720	14.013	23.000	0.550	1000.	1.	1200.	0	3
	DOWN	12.000	2.330	0.0	11.713	23.000	0.500	40.	1.	500.	1	1
14	UP	16.000	1.440	0.720	14.040	23.000	0.550	1000.	1.	1200.	0	3
	DOWN	12.000	2.330	0.0	11.740	23.000	0.500	40.	1.	500.	1	1
15	UP	16.000	1.440	0.720	14.013	23.000	0.550	1000.	1.	1200.	0	3
	DOWN	12.000	2.330	0.0	11.713	23.000	0.500	40.	1.	500.	1	1
16	UP	16.000	1.440	0.720	14.040	23.000	0.550	1000.	1.	1200.	0	3
	DOWN	12.000	2.330	0.0	11.740	23.000	0.500	40.	1.	500.	1	1
17	UP	16.000	1.440	0.720	14.013	23.000	0.550	1000.	1.	1200.	0	3
	DOWN	12.000	2.330	0.0	11.713	23.000	0.500	40.	1.	500.	1	1
18	UP	16.000	1.440	0.720	14.040	23.000	0.550	1000.	1.	1200.	0	3
	DOWN	12.000	2.330	0.0	11.740	23.000	0.500	40.	1.	500.	1	1
19	UP	16.000	1.440	0.720	14.013	23.000	0.550	1000.	1.	1200.	0	3
	DOWN	12.000	2.330	0.0	11.713	23.000	0.500	40.	1.	500.	1	1

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Table A-1b

EXAMPLE OF SUMMARY PRINTOUTS:
B. CARRIER-TO-NOISE RATIOS, INTERFERENCE
LEVELS AND CARRIER-TO-INTERFERENCE RATIOS

4/24/74 CASE 28 12°, 1CH, 27MHZ OSC VS 32°, 1200CH, 40MHZ FSH; SAT SEP=3,2,5,4,8

WANTED LINK	UP-LINK INTERFERENCE	UP-LINK C/N	DOWN-LINK INTERFERENCE	DOWN-LINK C/N	TOTAL INTERFERENCE	TOTAL C/N
1 NY TO LA	194.6	33.1	283.7	26.5	478.3	25.7
2 NY TO CHI	339.0	33.1	461.7	28.1	800.7	26.9
3 NY TO ATL	364.9	33.1	482.9	27.8	847.8	26.7
4 NY TO DAL	387.7	33.1	500.6	28.0	888.3	26.9
5 LA TO NY	334.8	33.6	567.6	25.9	902.3	25.2
6 LA TO CHI	253.7	33.6	411.5	28.1	665.2	27.0
7 LA TO ATL	278.5	33.6	301.0	27.4	579.5	26.5
8 LA TO DAL	445.0	33.6	469.4	28.2	914.4	27.1
9 CHI TO NY	289.4	35.5	545.4	26.6	834.8	26.1
10 CHI TO ATL	330.0	35.5	507.7	27.4	837.7	26.8
11 CHI TO DAL	316.1	35.5	455.3	28.2	771.5	27.5
12 CHI TO LA	180.8	35.5	255.5	26.8	436.2	26.3
13 NY TO 1NE	33.2	31.7	43.1	19.9	32.7	19.6
13 NY TO AB1	33.2	31.7	37.2	24.8	31.7	24.0
13 NY TO 1S	33.2	31.7	41.7	18.8	32.6	18.6
13 NY TO 1NW	33.2	31.7	26.2	17.7	25.4	17.5
13 NY TO 1W	33.2	31.7	29.2	22.5	27.7	22.0
13 NY TO 1SW	33.2	31.7	30.0	21.4	28.3	21.1
14 NY TO 1NE	33.3	31.7	46.6	19.9	33.1	19.6
14 NY TO AB1	33.3	31.7	37.6	24.8	31.9	24.0
14 NY TO 1S	33.3	31.7	44.7	18.8	33.0	18.6
14 NY TO 1NW	33.3	31.7	26.3	17.7	25.5	17.5
14 NY TO 1W	33.3	31.7	29.3	22.5	27.8	22.0
14 NY TO 1SW	33.3	31.7	30.2	21.4	28.4	21.1
15 CHI TO 2NE	30.8	31.5	30.1	19.6	27.4	19.3
15 CHI TO 2E	30.8	31.5	29.0	22.4	26.8	21.9
15 CHI TO 2SE	30.8	31.5	27.3	19.9	25.7	19.6
15 CHI TO AB2	30.8	31.5	34.2	24.8	29.2	24.0
15 CHI TO 2NW	30.8	31.5	27.3	18.4	25.7	18.2
15 CHI TO 2W	30.8	31.5	29.0	22.7	26.8	22.1
15 CHI TO 2SW	30.8	31.5	29.2	20.0	26.9	19.7
16 CHI TO 2NE	30.9	31.5	30.3	19.6	27.6	19.3
16 CHI TO 2E	30.9	31.5	29.1	22.4	26.9	21.9
16 CHI TO 2SE	30.9	31.5	27.4	19.9	25.8	19.6
16 CHI TO AB2	30.9	31.5	34.4	24.9	29.3	24.0
16 CHI TO 2NW	30.9	31.5	27.4	18.4	25.8	18.2
16 CHI TO 2W	30.9	31.5	29.1	22.7	26.9	22.1
16 CHI TO 2SW	30.9	31.5	29.3	20.0	27.0	19.7
17 DENV TO 3NE	31.3	31.8	28.9	19.2	26.9	19.0
17 DENV TO 3E	31.3	31.8	29.1	22.8	27.1	22.3

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along the interference path, and the values of carrier-to-noise ratio C/N. A small sample of the diagnostic type of printout for a fixed-satellite link is given in Table A-2a; the corresponding printout for a broadcasting-satellite link in Table A-2b.

Scope and Options

Although other signal types can be added, the program is presently limited to analog signals. Telephone channels must use frequency division multiplex (FDM) and frequency modulation (FM), and television channels must also employ FM. FDM/FM basebands must include 12 or more channels and employ rms modulation indices in the order of unity or larger.

Parabolic antennas are assumed but satellite antennas may be either elliptical or circular in cross section. The long dimensions of the footprint of an elliptical satellite antenna can be oriented in any desired direction. The direction is specified by the antenna aim point and a second point called the footprint point, or a default direction E-W through the aim point. Any of the several antenna sidelobe envelope patterns suggested by the CCIR for interference calculations in either service may be specified for any antenna.

Antenna pointing errors, amounting to 0.1 deg for satellites and 0.1 of the half-power beamwidth for earth stations, are included in all link calculations in such a way as to diminish wanted signals and enhance unwanted signals.

When polarized antennas are used to reduce interference on adjacent satellites and frequencies, the antenna gain products on interfering links are calculated without neglecting either of the two component terms. The cross-polarized pattern of an antenna is obtained by subtracting the polarization discrimination pattern from the assumed co-polarized pattern. Two polarization discrimination patterns are included; others can be added at will.

With broadcasting-satellite systems, performance must be satisfactory throughout the entire service area. Accordingly, the program includes the capability of sampling the carrier-to-noise and carrier-to-interference ratio at several locations as specified by the user for each satellite.

Table A-2a

EXAMPLE OF DETAILED "DIAGNOSTIC" PRINTOUT:
A. INDIVIDUAL INTERFERENCE CONTRIBUTIONS ON AN FDM/FM LINK

DOWN-LINK # 6, CHI, AT 41.90 -87.60 FROM SATELLITE AT -89.45
DOWN-LINK: I = 411.5 PWOP, C/N = 28.1 DB, C = -100.9 DBW, X/R SUM = -74.8 DBW
TOTAL I = 665.2 PWOP, TOTAL C/N = 27.0 DB

I(1) =	0.39 PWOP, X =	-155.61 DBW, RTC =	27.26 DB, GAIN PROD. =	21.45 DB
I(2) =	0.49 PWOP, X =	-154.54 DBW, RTC =	27.26 DB, GAIN PROD. =	22.53 DB
I(3) =	0.65 PWOP, X =	-153.35 DBW, RTC =	27.26 DB, GAIN PROD. =	23.72 DB
I(4) =	0.89 PWOP, X =	-152.01 DBW, RTC =	27.26 DB, GAIN PROD. =	25.06 DB
I(5) =	1.23 PWOP, X =	-150.56 DBW, RTC =	27.26 DB, GAIN PROD. =	26.22 DB
I(6) =	1.84 PWOP, X =	-148.83 DBW, RTC =	27.26 DB, GAIN PROD. =	27.96 DB
I(8) =	140.88 PWOP, X =	-129.99 DBW, RTC =	27.26 DB, GAIN PROD. =	46.80 DB
I(9) =	37.95 PWOP, X =	-135.68 DBW, RTC =	27.26 DB, GAIN PROD. =	41.28 DB
I(10) =	13.80 PWOP, X =	-140.08 DBW, RTC =	27.26 DB, GAIN PROD. =	36.88 DB
I(11) =	6.75 PWOP, X =	-143.18 DBW, RTC =	27.26 DB, GAIN PROD. =	33.77 DB
I(12) =	3.88 PWOP, X =	-145.59 DBW, RTC =	27.26 DB, GAIN PROD. =	31.37 DB
I(13) =	3.30 PWOP, X =	-145.09 DBW, RTC =	28.46 DB, GAIN PROD. =	31.98 DB
I(14) =	0.35 PWOP, X =	-145.09 DBW, RTC =	38.21 DB, GAIN PROD. =	31.98 DB
I(15) =	8.32 PWOP, X =	-141.08 DBW, RTC =	28.46 DB, GAIN PROD. =	35.88 DB
I(16) =	0.88 PWOP, X =	-141.08 DBW, RTC =	38.21 DB, GAIN PROD. =	35.88 DB
I(17) =	18.15 PWOP, X =	-137.69 DBW, RTC =	28.46 DB, GAIN PROD. =	39.17 DB
I(18) =	1.92 PWOP, X =	-137.69 DBW, RTC =	38.21 DB, GAIN PROD. =	39.17 DB
I(19) =	33.31 PWOP, X =	-135.05 DBW, RTC =	28.46 DB, GAIN PROD. =	41.73 DB
I(20) =	3.53 PWOP, X =	-135.05 DBW, RTC =	38.21 DB, GAIN PROD. =	41.73 DB

UP-LINK # 7, GROUND AT LA 34.10 -118.30 TO SATELLITE AT -106.55
UP-LINK: I = 278.5 PWOP, C/N = 33.5 DB, C = -88.7 DBW, X/R SUM = -64.3 DBW

I(1) =	0.57 PWOP, X =	-166.85 DBW, RTC =	27.26 DB, GAIN PROD. =	22.36 DB
I(2) =	0.72 PWOP, X =	-165.83 DBW, RTC =	27.26 DB, GAIN PROD. =	23.38 DB
I(3) =	0.93 PWOP, X =	-164.69 DBW, RTC =	27.26 DB, GAIN PROD. =	24.51 DB
I(4) =	1.25 PWOP, X =	-163.40 DBW, RTC =	27.26 DB, GAIN PROD. =	25.79 DB
I(5) =	1.76 PWOP, X =	-161.93 DBW, RTC =	27.26 DB, GAIN PROD. =	27.26 DB
I(6) =	2.61 PWOP, X =	-160.21 DBW, RTC =	27.26 DB, GAIN PROD. =	28.99 DB
I(8) =	199.18 PWOP, X =	-141.38 DBW, RTC =	27.26 DB, GAIN PROD. =	47.94 DB
I(9) =	35.02 PWOP, X =	-148.93 DBW, RTC =	27.26 DB, GAIN PROD. =	40.42 DB
I(10) =	12.71 PWOP, X =	-153.33 DBW, RTC =	27.26 DB, GAIN PROD. =	36.06 DB
I(11) =	6.21 PWOP, X =	-156.45 DBW, RTC =	27.26 DB, GAIN PROD. =	32.98 DB
I(12) =	3.57 PWOP, X =	-158.86 DBW, RTC =	27.26 DB, GAIN PROD. =	30.61 DB
I(13) =	17.18 PWOP, X =	-150.83 DBW, RTC =	28.46 DB, GAIN PROD. =	38.38 DB
I(14) =	1.82 PWOP, X =	-150.83 DBW, RTC =	38.21 DB, GAIN PROD. =	38.38 DB
I(15) =	14.83 PWOP, X =	-151.47 DBW, RTC =	28.46 DB, GAIN PROD. =	37.76 DB
I(16) =	1.57 PWOP, X =	-151.47 DBW, RTC =	38.21 DB, GAIN PROD. =	37.76 DB
I(17) =	0.24 PWOP, X =	-169.31 DBW, RTC =	28.46 DB, GAIN PROD. =	19.93 DB
I(18) =	0.03 PWOP, X =	-169.31 DBW, RTC =	38.21 DB, GAIN PROD. =	19.93 DB
I(19) =	0.70 PWOP, X =	-164.75 DBW, RTC =	28.46 DB, GAIN PROD. =	24.51 DB
I(20) =	0.07 PWOP, X =	-164.75 DBW, RTC =	38.21 DB, GAIN PROD. =	24.51 DB

DOWN-LINK # 7, ATL, AT 33.70 -84.40 FROM SATELLITE AT -106.55
DOWN-LINK: I = 301.0 PWOP, C/N = 27.4 DB, C = -101.6 DBW, X/R SUM = -76.8 DBW
TOTAL I = 579.5 PWOP, TOTAL C/N = 26.5 DB

I(1) =	0.31 PWOP, X =	-156.47 DBW, RTC =	27.26 DB, GAIN PROD. =	20.64 DB
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Table A-2b

EXAMPLE OF DETAILED "DIAGNOSTIC" PRINTOUT:
B. INDIVIDUAL INTERFERENCE CONTRIBUTIONS ON A TV/FM LINK

QC/X(1) =	64.72 DB, X =	-151.25 DBW, Q =	6.13 DB, GAIN PROD. =	25.72 DB
QC/X(2) =	63.14 DB, X =	-149.67 DBW, Q =	6.13 DB, GAIN PROD. =	27.30 DB
QC/X(3) =	61.30 DB, X =	-147.83 DBW, Q =	6.13 DB, GAIN PROD. =	29.14 DB
QC/X(4) =	59.08 DB, X =	-145.61 DBW, Q =	6.13 DB, GAIN PROD. =	31.36 DB
QC/X(5) =	57.61 DB, X =	-144.13 DBW, Q =	6.13 DB, GAIN PROD. =	32.71 DB
QC/X(6) =	53.89 DB, X =	-140.41 DBW, Q =	6.13 DB, GAIN PROD. =	36.43 DB
QC/X(7) =	57.19 DB, X =	-143.72 DBW, Q =	6.13 DB, GAIN PROD. =	33.13 DB
QC/X(8) =	60.10 DB, X =	-146.63 DBW, Q =	6.13 DB, GAIN PROD. =	30.21 DB
QC/X(9) =	59.58 DB, X =	-146.11 DBW, Q =	6.13 DB, GAIN PROD. =	30.79 DB
QC/X(10) =	61.46 DB, X =	-147.99 DBW, Q =	6.13 DB, GAIN PROD. =	28.92 DB
QC/X(11) =	63.05 DB, X =	-149.58 DBW, Q =	6.13 DB, GAIN PROD. =	27.33 DB
QC/X(12) =	64.43 DB, X =	-150.96 DBW, Q =	6.13 DB, GAIN PROD. =	25.94 DB
QC/X(13) =	34.65 DB, X =	-127.31 DBW, Q =	0.0 DB, GAIN PROD. =	49.66 DB
QC/X(14) =	134.65 DB, X =	-127.31 DBW, Q =	100.00 DB, GAIN PROD. =	49.66 DB
QC/X(16) =	99.85 DB, X =	-92.51 DBW, Q =	100.00 DB, GAIN PROD. =	84.39 DB
QC/X(17) =	33.67 DB, X =	-126.32 DBW, Q =	0.0 DB, GAIN PROD. =	50.54 DB
QC/X(18) =	133.67 DB, X =	-126.32 DBW, Q =	100.00 DB, GAIN PROD. =	50.54 DB
QC/X(19) =	43.69 DB, X =	-136.35 DBW, Q =	0.0 DB, GAIN PROD. =	40.50 DB
QC/X(20) =	143.69 DB, X =	-136.35 DBW, Q =	100.00 DB, GAIN PROD. =	40.50 DB

UP-LINK # 15, GROUND AT CHI 41.90 -87.60 TO SATELLITE AT -96.75
UP-LINK: QC/X = 30.8 DB, C/N = 31.5 DB, C = -92.7 DBW, X/Q SUM = -123.5 DBW

QC/X(1) =	58.05 DB, X =	-160.35 DBW, Q =	6.13 DB, GAIN PROD. =	29.12 DB
QC/X(2) =	58.02 DB, X =	-160.32 DBW, Q =	6.13 DB, GAIN PROD. =	29.14 DB
QC/X(3) =	57.96 DB, X =	-160.26 DBW, Q =	6.13 DB, GAIN PROD. =	29.19 DB
QC/X(4) =	55.71 DB, X =	-158.01 DBW, Q =	6.13 DB, GAIN PROD. =	31.43 DB
QC/X(5) =	52.89 DB, X =	-155.19 DBW, Q =	6.13 DB, GAIN PROD. =	34.26 DB
QC/X(6) =	49.09 DB, X =	-151.39 DBW, Q =	6.13 DB, GAIN PROD. =	38.05 DB
QC/X(7) =	52.09 DB, X =	-154.38 DBW, Q =	6.13 DB, GAIN PROD. =	35.12 DB
QC/X(8) =	54.97 DB, X =	-157.27 DBW, Q =	6.13 DB, GAIN PROD. =	32.26 DB
QC/X(9) =	57.23 DB, X =	-159.53 DBW, Q =	6.13 DB, GAIN PROD. =	30.02 DB
QC/X(10) =	57.66 DB, X =	-159.96 DBW, Q =	6.13 DB, GAIN PROD. =	29.62 DB
QC/X(11) =	57.67 DB, X =	-159.97 DBW, Q =	6.13 DB, GAIN PROD. =	29.64 DB
QC/X(12) =	57.68 DB, X =	-159.98 DBW, Q =	6.13 DB, GAIN PROD. =	29.66 DB
QC/X(13) =	30.36 DB, X =	-138.78 DBW, Q =	0.0 DB, GAIN PROD. =	50.67 DB
QC/X(14) =	130.36 DB, X =	-138.78 DBW, Q =	100.00 DB, GAIN PROD. =	50.67 DB
QC/X(16) =	98.32 DB, X =	-106.75 DBW, Q =	100.00 DB, GAIN PROD. =	82.71 DB
QC/X(17) =	48.62 DB, X =	-157.05 DBW, Q =	0.0 DB, GAIN PROD. =	32.42 DB
QC/X(18) =	148.62 DB, X =	-157.05 DBW, Q =	100.00 DB, GAIN PROD. =	32.42 DB
QC/X(19) =	57.32 DB, X =	-165.75 DBW, Q =	0.0 DB, GAIN PROD. =	23.74 DB
QC/X(20) =	157.32 DB, X =	-165.75 DBW, Q =	100.00 DB, GAIN PROD. =	23.74 DB

DOWN-LINK # 15, 2NE, AT 47.50 -86.50 FROM SATELLITE AT -96.75
DOWN-LINK: QC/X = 30.1 DB, C/N = 19.6 DB, C = -108.4 DBW, X/Q SUM = -138.5 DBW
TOTAL C/X = 27.4 DB, TOTAL C/N = 19.3 DB

QC/X(1) =	60.10 DB, X =	-159.56 DBW, Q =	6.13 DB, GAIN PROD. =	29.71 DB
QC/X(2) =	60.12 DB, X =	-159.58 DBW, Q =	6.13 DB, GAIN PROD. =	29.68 DB
QC/X(3) =	60.13 DB, X =	-159.60 DBW, Q =	6.13 DB, GAIN PROD. =	29.65 DB
QC/X(4) =	58.17 DB, X =	-157.63 DBW, Q =	6.13 DB, GAIN PROD. =	31.61 DB
QC/X(5) =	55.40 DB, X =	-154.86 DBW, Q =	6.13 DB, GAIN PROD. =	34.38 DB
QC/X(6) =	51.66 DB, X =	-151.12 DBW, Q =	6.13 DB, GAIN PROD. =	38.12 DB
QC/X(7) =	54.91 DB, X =	-154.17 DBW, Q =	6.13 DB, GAIN PROD. =	34.95 DB
QC/X(8) =	57.81 DB, X =	-157.28 DBW, Q =	6.13 DB, GAIN PROD. =	32.07 DB
QC/X(9) =	60.10 DB, X =	-159.56 DBW, Q =	6.13 DB, GAIN PROD. =	29.81 DB

DETAILED DESCRIPTION

The program consists of a main routine and three subroutines that will be described separately with the aid of the internal statement numbers printed along the left-hand margin of the program listing. (A complete listing of the program is given at the end of this Appendix.) The equations used in the program are indicated by citing their identifying numbers as assigned in the text of the report.

Main Routine

The inputs to the MAIN routine are identified in Table A-3. As noted previously, the input data constitute a detailed description of the systems, their geographical deployment, the links they provide, and the signals carried on these links.

For each link of the fixed-satellite systems, the MAIN routine then computes and prints the output interference in the worst telephone channel in pWOp. This is done by summing the individual contributions entering the uplink and downlink of the link, using values of the receiver transfer constant computed by subroutine "RTC," the effective diameter of elliptical satellite antennas computed by subroutine "ELLPS," and the antenna gain products computed by subroutine "GAIN."

Similarly, for each link of the broadcasting-satellite systems, the MAIN routine computes and prints the effective carrier-to-interference ratio at the input to the receivers at the selected receiving sites. The details of the computation are given in the following step-by-step description.

Referring to the listing at the end of the Appendix, internal statements (IS) 1-3 give the dimensions of the input and derived parameters listed in Table A-3. The indicated dimensions of 52 satellites, 35 earth stations and satellite antenna aim points, and 120 links and sublinks are purely arbitrary and can be increased to much higher values if desired.

IS 5-11 define frequently needed constants and conversion factors.

IS 15-91 read the input data on link characteristics (see Table A-3) and store them in the various arrays. In particular, IS 26-58 apply to the fixed-satellite links, and IS 60-91 accommodate the broadcasting satellite links and sublinks.

Table A-3

INPUTS TO MAIN PROGRAM

Dimensions of problem

NLNK = number of links
 NS = number of satellites
 NFIX = number of satellites for fixed-satellite service
 MG = number of ground stations
 NGRCV = total number of ground receiving locations to be sampled on
 broadcasting-satellite downlinks

Locations of terminals (north latitude and east longitude are positive)

RS(I) = longitude (deg) of Ith satellite, I = 1, ..., NS
 ELG(I) = latitude (deg) of Ith ground station or aim point, I = 1, ..., MG
 RG(I) = longitude (deg) of Ith ground station or aim point, I = 1, ..., MG
 NAM(I) = name of city associated with Ith fixed-satellite ground
 station, I = 1, ..., MG
 CHR(I) = code name of locations sampled on broadcasting-satellite
 downlinks $1 \leq I \leq \text{NLNK}$
 FTPTL = latitude (deg) of footprint orientation point for elliptical
 fixed-satellite antennas
 FTPTR = longitude (deg) of footprint orientation point for elliptical
 fixed-satellite antennas
 FPL(I) = Same as FTPTL but for broadcasting satellites, I = (NFIK+1), ..., NS
 FPR(I) = Same as FTPTR but for broadcasting satellites, I = (NFIK+1), ..., NS

Description of link I, $1 \leq I \leq \text{NLNK}$

FG(I) = carrier frequency (GHz) of ground transmitter (uplink fre-
 quencies)
 FS(I) = carrier frequency (GHz) of satellite transmitter (downlink
 frequencies)
 PWU(I) = power (dBW) of uplink
 PWD(I) = power (dBW) of downlink
 WRFU(I) = uplink rf signal bandwidth
 WRFD(I) = downlink rf signal bandwidth
 UNO(I) = uplink number of voice channels
 DNO(I) = downlink number of voice channels
 DGT(I) = diameter (ft) of ground transmitting antenna
 DGR(I) = diameter (ft) of ground receiving antenna (ft)
 ETAG(I) = efficiency of ground antennas
 DST(I) = diameter (ft) of satellite transmitting antenna^a (ft)
 DSR(I) = diameter (ft) of satellite receiving antenna^a (ft)
 ETAS(I) = efficiency of satellite antennas
 ELPT(I) = minor axis (ft) of elliptical satellite transmitting antenna^b
 ELPR(I) = minor axis (ft) of elliptical satellite receiving antenna^b
 TUI = system temperature (°K) for uplink

Table A-3 (continued)

TDI = system temperature ($^{\circ}$ K) for fixed-satellite downlink
TDSI = system temperature ($^{\circ}$ K) for broadcasting-satellite downlink
IAM(I) = index of satellite antenna aim point (regarded as an earth station)
IS(I) = index number of satellite for Ith link
IGU(I) = index of ground uplink station for Ith link
IGD(I) = index of ground downlink station for Ith link
IPLU(I) = polarization of uplink (Ith link)
IPLD(I) = polarization of downlink (Ith link)
IRUTU(I) = flag, uplink (0 = FDM/FM, 1 = TV/FM) (Ith link)
IRVTU(I) = flag, downlink (0 = FDM/FM, 1 = TV/FM) (Ith link)
IRVTD(I) = number of ground receivers for Ith broadcasting-satellite link.

Flags for all links

IBW = Cross-polarization pattern (1 = best, 2 = worst)
ILLPT = flag for orientation of elliptical antenna on fixed-satellites
(0 = major axis of antenna footprint is EW through aim point,
1 = major axis of footprint passes through aim point and
footprint point), tending basically E-W)
JLLPT = same as ILLPT but for broadcasting satellites (0, 1 = same as
ILLPT, 2 = same as 1 but major axis tends basically
N-S)
KPRNT = flag for printing (0 = print all; 1 = summary only)

^aMajor axis if elliptical.

^bZero if circular.

IS 93-115 compute and store in square arrays all relevant values of path length and the intersatellite and inter-earth-station distances which will be needed for the calculation of off-axis angles and path losses. The formulas used are given in Eqs. (70)-(74) of Sec. IV.

IS 119-147 compute uplink wanted signal power CU for link I using subroutines ELLPS and GAIN. Equations (42) and (45) with $J=I$ are used for CU, and Eq. (71) is used for the off-axis angle DEL in IS 142 (program step 37). Figure A-1a shows the path geometry and the notation used in the program.

IS 150-168 compute in similar fashion the uplink unwanted signal power X from link j into link i using Eqs. (42) and (45) for X and Eqs. (71) and (73) for DEL and GAM, respectively. Again, Fig. A-1a shows the path geometry and notation.

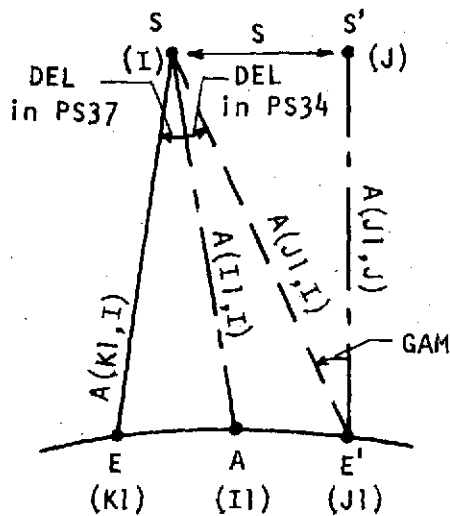
IS 169 and 170 use subroutine RTC to compute the receiver transfer characteristic R or sensitivity factor Q and then compute the uplink output interference contribution from link j into link i using the equations identified in the description of that subroutine.

IS 172-183 commands the printing of the individual uplink interference contributions, along with other data pertinent to the uplink interference paths.

IS 185-199 compute and store summary results on uplink noise and interference, and print them on demand. In particular, IS 187 computes the total uplink interference UI after the individual contributions to X/R or X/Q have been computed for all values of j and accumulated as XSU. The results are stored for the summary printout by IS 191 for fixed-satellite uplinks and by IS 195 and 196 for broadcasting-satellite uplinks.

IS 200-239 compute the downlink wanted signal power CD for link i in exactly the same fashion as IS 119-147 compute CU. In the case of broadcasting satellites, the calculations are repeated for each of several sublinks (different receiving sites) on each downlink as commanded by the do-loop starting at IS 206. The path geometry and index conventions are shown in Fig. A-1b.

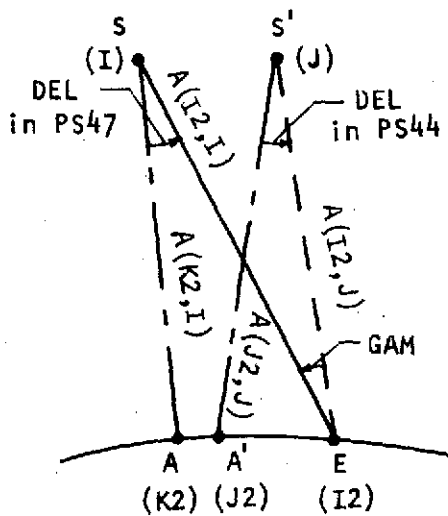
IS 242-269 and IS 270 and 271, respectively, perform the same functions for downlink interference from link j into link i as do IS 150-168 and IS 169 and 170 do for uplink interference. The path geometry and notation are also shown in Fig. A-1b.



a. Uplink signal paths

E = Wanted earth station
 S = Wanted satellite
 A = Aim point of receiving antenna on S
 E' = Interfering earth station
 S' = Satellite used by E

———— ES = Wanted signal path
 - - - - E'S = Unwanted signal path
 - - - - SA, E'S' = Antenna beam axes



b. Downlink signal paths

S = Wanted satellite
 E = Wanted earth station
 A = Aim point of transmitting antenna on S
 S' = Interfering satellite
 A' = Aim point of transmitting antenna on S'

———— SE = Wanted signal path
 - - - - S'E = Unwanted signal path
 - - - - SA, S'A' = Antenna beam axes

Fig. A-1--Indices used to identify signal paths in computer program

IS 273-282 command the printing of the individual downlink interference contributions and certain data on the downlink interference paths.

IS 284-302 compute and store summary results on downlink and total noise and interference, and print them on demand. In particular, IS 286 computes the aggregate downlink interference DI after the individual contributions to X/R have been computed for all values of j and accumulated as XSD. The results are stored for the summary printout by IS 291 for fixed satellites and by IS 296 and 298 for broadcasting satellites. The total interference (uplink plus downlink) is computed and stored by IS 292 for fixed-satellite links and by 297 and 299 for broadcasting-satellite links.

IS 307-319 print a table which summarizes the input parameters for each link and lists the satellite locations.

IS 320-335 print the summary table of interference and carrier-to-noise ratio (uplink, downlink, and total) for each link and sublink.

IS 336-341 provide a means for running multiple cases and for skipping duplicate inputs where possible.

The Gain-Product Subroutine

Subroutine GAIN computes the gain product for the uplink or downlink as specified by the inputs defined in Table A-4. In the case of an uplink, the input TH1 is the off-axis angle at the earth-station transmitting antenna and TH2 is the off-axis angle at the satellite receiving antenna. For a downlink, TH1 is the off-axis angle at the earth-station receiving antenna and TH2 the off-axis angle at the satellite transmitting antenna. In either case, the link may be a wanted signal path or an unwanted signal path.

Regardless of the nature of the path, four antenna patterns are involved in the computation of the antenna gain product. These are designated as follows in the subroutine:

- G(1) The co-polarized pattern at the earth station
- G(2) The co-polarized pattern at the satellite
- G(3) The cross-polarized pattern at the earth station
- G(4) The cross-polarized pattern at the satellite

Table A-4

INPUTS TO GAIN SUBROUTINE

TH1 = off-axis angle at earth station (radians)
TH2 = off-axis angle at satellite (radians)
I1 = index indicating which pattern used at earth station
I2 = index indicating which pattern used at satellite
IPL1 = index indicating which polarization used at earth station^a
IPL2 = index indicating which polarization used at satellite^a
F1 = frequency (GHz) of earth-station transmitter or receiver
F2 = frequency (GHz) of satellite receiver or transmitter
D1 = diameter of earth-station antenna (ft)
D2 = N-S dimension^b of satellite antenna (diameter if circular) (ft)
DX = E-W dimension^b of satellite antenna (zero if circular) (ft)
DLPS = effective diameter of elliptical antenna (ft) from ELLPS
subroutine
IBW = flag indicating whether best or worst cross-polarized
pattern is to be used

^a(0 = horizontal, 1 = vertical).

^bThe N-S and E-W designations are approximate.

If the earth-station and satellite antennas have opposite polarizations, the gain product is computed at IS 118 as

$$GANE = G(1) \times G(4) + G(2) \times G(3)$$

If the polarization is the same, the gain product computed at IS 120 as

$$GANE = G(1) \times G(2)$$

The intervening steps in the subroutine compute the patterns $G(1)$, $G(2)$, $G(3)$, and $G(4)$ in succession by matching them to the CCIR pattern envelopes specified by input indices $I1$ and $I2$. In particular, IS 17-29 apply to the main lobe; all the rest apply to the sidelobe envelopes. Note that IS 31 can be understood by referring to the list of pattern flag values and indentifications given in the main program after IS 91.

SUBROUTINE ELLPS

This subroutine accepts the input parameters displayed in Table A-5 and computes the effective "diameter" DLPS in feet of an elliptical antenna for use in calculating the gain of that antenna in the direction of the specified earth station.

The equations used in the subroutine are Eqs. (65) through (69). The correspondence between symbols used in the equations and names used in the subroutine is shown in the partial cross-reference table given below

$a_1 =$	XAS	$b_1 =$	YAS		
$a_2 =$	XGS	$b_2 =$	YGS		
$\ell_1 =$	L1	$m_1 =$	M1	$n_1 =$	N1
$\ell_2 =$	L2	$m_2 =$	M2	$n_2 =$	N2
$r_S =$	RS				
$r_A =$	RA	$\ell_A =$	ELA		
$r_E =$	RG	$\ell_E =$	ELG		

Table A-5

INPUTS TO ELLPS SUBROUTINE

RS = Longitude of satellite (deg E)
ELA = Latitude of satellite antenna aim point (deg N)
RA = Longitude of satellite antenna aim point (deg E)
ELG = Latitude of earth station (deg N)
RG = Longitude of earth station (deg E)
D1 = N-S dimension of satellite antenna (ft)
D2 = E-W dimension of satellite antenna (ft)
FTP TL = latitude of footprint point used with aim point to determine
 orientation of one axis of satellite antenna footprint
FTP TR = longitude of footprint point used with aim point to determine
 orientation of one axis of satellite antenna footprint
ILLPT = flag to identify manner and direction of orientation of one axis:
 = 0: D2 axis is made tangent to the parallel of latitude
 through the aim point
 = 1: D2 axis passes through aim point and footprint point
 = 2: D1 axis passes through aim point and footprint point

Note: The last three parameters are transmitted to the subroutine by
the common statement.

When the orientation of the satellite antenna footprint is determined through specification of a footprint point (ILLPT = 1 or 2), the direction numbers L1, M1, N1 for the formula in IS 44 are computed in IS 28-36 in the same fashion as L2, M2, N2.

SUBROUTINE RTC

This subroutine computes the receiver transfer characteristic R or sensitivity factor Q as a pure numeric from the inputs shown in Table A-6. The equations used for the computation depend on the combination of wanted and unwanted signal as specified by the flags IR1 and IR2. Using the subscripts F, T and N for FDM/FM, TV/FM, and noise respectively, the calculations are carried out as follows.

IS 23 and 29 compute R_{FF} using Eq. (24).

IS 28 and 29 compute R_{FT} using Eq. (29).

IS 31 computes R_{FN} using Eq. (4).

IS 44 and 45 compute Q_{TT} using Eq. (35).

IS 53 and 45 compute Q_{TF} using Eq. (36).

Table A-6

INPUTS TO SUBROUTINE RTC

N1 = number of telephone channels on wanted carrier
N2 = number of telephone channels on unwanted carrier
W1 = rf bandwidth of wanted carrier (MHz)
W2 = rf bandwidth of unwanted carrier (MHz)
F1 = carrier frequency of wanted carrier (GHz)
F2 = carrier frequency of unwanted carrier (GHz)
IR1 = flag for type of wanted signal (0 = FDM/FM, 1 = TV/FM)
IR2 = flag for type of unwanted signal (0 = FDM/FM, 1 = TV/FM,
2 = Noise)
SPØNW = output picture-signal-to-weighted noise objective (dB)
for wanted TV/FM signal

```

0001      INTEGER*4 CHR
0002      DIMENSION SPS(52,52),AS(52,52),A(52,52),RS(52),ELG(35),RG(35)
          1,DGT(60),DGR(120),DST(60),DSR(60),ELPT(60),ELPR(60)
          2, FG(50),FS(60),PWU(60),PWD(60),WRFU(60),WRFD(60),UNO(60),DNO(60)
          3,ETAG(120),ETAS(60),FPL(60),FPR(60)
          4,IAM(60),IS(60),IGU(60),IGD(120),IPLU(60),IPLD(60)
          5,IPTGU(60),IPTGD(120),IPATS(60),IRVTU(60),IPVTD(60),IGRCV(60)
          6,VIU(120),VID(120),VTOT(120),CVNUI(120),CVND(120),TCVN(120)
0003      DIMENSION NAM(50),TITL(20),CHR(120)
0004      COMMON G(4),FTPTL,FTPTR,JIFPT
0005      DATA D/6.617/,RPD/1.745329E-2/,ERUMS/4.0591E13/
0006      DATA C,CS/3.,.09/,BDL/1.3806E-17/
0007      PI45=16.*9.869604
0008      D2=2.*D
0009      DSP=D*D+1.
0010      PE=.1*PPD
0011      PEN=-PE
0012      10 CONTINUE
0013      NCAS=1
0014      NCSX=1
0015      READ 1,NLNK,NS,MG,IRW,ILLPT,NGRCV,NFIX,KPNT,JLLPT
0016      1 FORMAT(15I5)
0017      IF(NLNK.EQ.0) CALL EXIT
0018      IF(NGRCV.EQ.0) NGRCV=NLNK
0019      READ 3,TITL
0020      3 FORMAT(20A4)
0021      READ 2,(RS(I),I=1,NS)
0022      2 FORMAT(6E12.4)
0023      READ 3,(NAM(I),I=1,MG)
0024      READ 2,(ELG(I),RG(I),I=1,MG)
0025      IF(NFIX.EQ.0) GO TO 280
0026      READ 2,ELPTI,ELPRI
0027      IF(ILLPT.NE.0) READ 2,FTPTL,FTPTR
0028      VTPTL=FTPTL
0029      VTPTR=FTPTR
0030      READ 2,      DGTI ,FGI ,PWUI ,WRFUI ,UNOI ,DGR
0031      READ 2,      DSTI ,FSI ,PWDI ,WRFDI ,DNOI ,DSRI
0032      280 CONTINUE
0033      READ 2,ETAGI,ETASI
0034      READ 2,TUI,TDI,TDSI
0035      DO 12 I=1,NLNK
0036      READ 1,IAM(I),IS(I),IGU(I),IGD(I),IPLU(I),IPLD(I)
          1,IPTGU(I),IPTGD(I),IPATS(I),IRVTU(I),IRVTD(I),IGRCV(I)
0037      12 CONTINUE
0038      IF(NFIX.EQ.0) GO TO 290
0039      DO 160 I=1,NFIX
0040      FG(I)=FGI
0041      FS(I)=FSI
0042      K=IGD(I)
0043      CHR(I)=NAM(K)
0044      ELPT(I)=ELPTI
0045      ELPR(I)=ELPRI
0046      DST(I)=DSTI
0047      DSR(I)=DSRI
0048      DGT(I)=DGTI
0049      DGR(I)=DGR
0050      ETAG(I)=ETAGI
0051      ETAS(I)=ETASI

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ORIGINAL PAGE IS
OF POOR QUALITY

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0052      WRFU(I)=WRFUI
0053      WRFD(I)=WRFDI
0054      UNO(I)=UNOI
0055      DNO(I)=DNOI
0056      PWU(I)=10.**(.1*PWUI)
0057      PWD(I)=10.**(.1*PWDI)
0058      160 CONTINUE
0059      290 CONTINUE
0060      READ 2,ELPTI ,ELPRI
0061      N1=NFIX+1
0062      IF(JLLPT.NE.O) READ 2,(FPL(I),FPR(I),I=N1,NS)
0063      READ 2,      DGTI ,FGI ,PWUI ,WRFUI ,UNOI ,DGR1
0064      READ 2,      DSTI ,FSI ,PWDI ,WRFDI ,DNOI,DSRI
0065      N2=NFIX+NGRCV
0066      READ 3,(CHRI(I),I=N1,N2)
0067      READ 1,IPTGDI,IPTSU
0068      READ 1,      (IGDI(I),I=N1,N2)
0069      DO 162 I=N1,NLNK
0070      ELPT(I)=ELPTI
0071      ELPR(I)=ELPRI
0072      DST(I)=DSTI
0073      DSR(I)=DSRI
0074      DGT(I)=DGTI
0075      ETAS(I)=ETASI
0076      IPL=I+1-NFIX
0077      DLFCN=IPL-2*(IPL/2)
0078      DELF=DLFCN*.02
0079      FSI(I)=FSI+DELF
0080      FG(I)=FGI+DELF
0081      WRFU(I)=WRFUI
0082      WRFD(I)=WRFDI
0083      UNO(I)=UNOI
0084      DNO(I)=DNOI
0085      PWU(I)=10.**(.1*PWUI)
0086      PWD(I)=10.**(.1*PWDI)
0087      162 CONTINUE
0088      DO 161 I=N1,N2
0089      IPTGD(I)=IPTGDI
0090      ETAG(I)=ETAGI
0091      161 DGR(I)=DGR1

C
C      ****      KEY TO ANTENNA PATTERN FLAG
C      **      EARTH STATIONS, SIDE LOBE, CO-POLARIZED
C      FLAG = 1:  BROADCAST SATELLITE SERVICE, COMMUNITY RECEPTION
C      FLAG = 2:  BROADCAST SATELLITE SERVICE, INDIVIDUAL RECEPTION
C      FLAG = 3:  FIXED SATELLITE SERVICE
C      **      SATELLITES, SIDE LOBE, CO-POLARIZED
C      **      BROADCAST SATELLITE SERVICE
C      FLAG = 4:  NO LOBE CONTROL
C      FLAG = 5:  NORMAL LOBE CONTROL
C      FLAG = 6:  LIMIT OF SIDE-LOBE CONTROL
C      FLAG = 7:  ** FIXED SATELLITE SERVICE
C
C      ****      KEY TO RTC FLAG (IRVTU AND IRVTD)
C      FLAG = 0:  VOICE CHANNELS
C      FLAG = 1:  TV
C      FLAG = 2:  UNWANTED SIGNAL IS NOISE (2ND FLAG ONLY)

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0092      300 CONTINUE
0093      DO 25 I=2,NS
0094      SPS(I,1)=0.
0095      IM=I-1
0096      DO 25 J=1,IM
0097      S=D2*SIN(.5*(RS(J)-RS(I))*RPD)
0098      25 SPS(J,I)=S*S
0099      DO 30 I=1,MO
0100      SPS(I,1)=0.
0101      IM=I-1
0102      COSL=COS(ELG(I)*RPD)
0103      SINL=SIN(ELG(I)*RPD)
0104      RGIR=RG(I)*RPD
0105      IF(I.EQ.1) GO TO 28
0106      DO 27 J=1,IM
0107      COSB=COSL*COS(ELG(J)*RPD)*COS(RGIR-RG(J)*RPD)+SINL*SIN(ELG(J)*RPD)
0108      27 SPS(1,J)=2.*11.-COSB)
0109      28 DO 30 J=1,NS
0110      COSA=COSL*COS(RGIR-RS(J)*RPD)
0111      AA=OSP-D2*COSA
0112      AS(I,J)=AA
0113      AQ=SQRT(AA)
0114      A(I,J)=AQ
C      ***** FIRST INDEX IS G.S. #, SECOND INDEX IS SAT.#
0115      30 CONTINUE
0116      KRMX=0
0117      IF(KPRNT.EQ.0) PRINT 54,TITL
0118      DO 60 II=1,NLENK
0119      JIFPT=0
0120      IF(ILLPT.EQ.0) GO TO 131
0121      JIFPT=ILLPT
0122      FTPTR=VTPTR
0123      FTPTL=VTPTL
0124      131 CONTINUE
0125      I=IS(II)
0126      K1=IGU(II)
0127      I1=IAM(II)
0128      AQ=A(I1,I)
0129      AA=AS(I1,I)
0130      GAM=0.
0131      DEL=0.
0132      F1=FG(II)
0133      IPAT1=IPTGU(II)
0134      IPAT2=IPATS(II)
0135      DLPS=OSR(II)
0136      IF(K1.EQ.I1) GO TO 38
0137      IF(ELPR(II).NE.0.) CALL ELLPS(RS(I),RG(I1),ELG(I1),RG(K1),ELG(K1),
1 DSP(II),ELPR(II),DLPS)
0138      IF(K1.GT.I1) GO TO 36
0139      PS=SPS(I1,K1)
0140      GO TO 37
0141      36 PS=SPS(K1,I1)
0142      37 DEL=ARCCOS((AS(K1,I)+AA-PS)/(A(K1,I)*AQ*2.))
0143      38 CALL GAIN(GAM,DEL,IPAT1,IPAT2,1,1,F1,PE,DGT(II),OSR(II),ELPR(II),
1 DLPS,ETAG(II),ETAS(II),IRW,GANE)
0144      CU=GANE*PWU(II)*CS/(PI4S*AA*F1**2) /EPUMS
0145      CVNRU=BOL*TOI*WRFU(II)/CU
0146      CVNUI=-10.*ALOG10(CVNRU)

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0147      CVNU(I)=CVNUI
0148      XSU=0.
0149      DO 35 JJ=1,NLNK
0150      IF(JJ.EQ.1) GO TO 35
0151      J=IS(JJ)
0152      J1=IGU(JJ)
0153      A2=2.*A(J1,1)
0154      ASX=AS(J1,1)
0155      IF(J.GT.1) GO TO 31
0156      SS=SPS(J,1)
0157      GO TO 32
0158      31 SS=SPS(I,J)
0159      32 IF(J1.GT.1) GO TO 33
0160      PS=SPS(I1,J1)
0161      GO TO 34
0162      33 PS=SPS(J1,1)
0163      34 DEL=ARCCOS((AA+ASX-PS)/(AQ*A2))
0164      GAM=ARCCOS((ASX+AS(J1,J)-SS)/(AI(J1,J)*A2))
0165      IF(ELPR(I1).NE.0.) CALL ELLPS(RS(I),RG(I1),ELG(I1),RG(J1),ELG(J1),
0166      1 DSR(I1),ELPR(I1),DLPS)
0167      IPAT1=IPTGU(IJJ)
0168      CALL GAIN(GAM,DEL,IPAT1,IPAT2,IPLU(IJJ),IPLU(I1),F1,PEN,
0169      1 DGT(JJ),DSR(I1),ELPR(I1),DLPS,ETAG(JJ),ETAS(I1),IBW,GANE)
0170      X=PWU(JJ)*CS*GANE/(PI4S*ASX*F1*F1)/ERUMS
0171      CALL RTC(UND(I1),UND(IJJ),WRFU(I1),WRFU(JJ),FG(I1),FG(JJ)
0172      1,IRVTU(I1),IRVTU(IJJ),SPONW,R)
0173      XSU=XSU+X/R
0174      IF(KPRNT.NE.0) GO TO 35
0175      EI=X/(R*CU)
0176      RD=10.*ALOG10(R)
0177      XDB=10.*ALOG10(X)
0178      GDB=10.*ALOG10(GANE)
0179      IF(IRVTU(I1).EQ.1) GO TO 135
0180      RDB=RDB+90.
0181      PRINT 51,JJ,EI,XDB,RDB,GDB
0182      51 FORMAT(10X,' I',I2,' =',F10.2,' PWOP, X =',F10.2,' DBW, RTC =',
0183      1 F10.2,' DB, GAIN PROD. =',F10.2,' DB')
0184      GO TO 35
0185      135 EI=-10.*ALOG10(EI)
0186      PRINT 52,JJ,EI,XDB,RDB,GDB
0187      52 FORMAT(9X,' QC/XI',I2,' =',F10.2,' DB, X =',F10.2,' DBW, Q =',F10
0188      1,2,' DB, GAIN PROD. =',F10.2,' DB')
0189      35 CONTINUE
0190      IF(KPRNT.EQ.0)
0191      1 PRINT 55,I1,NAM(K1),ELG(K1),RG(K1),RS(I1)
0192      55 FORMAT(/' UP-LINK #',I3,' , GROUND AT',A5,2F8.2,' TO SATELLITE AT',
0193      1 F8.2)
0194      UI=XSU/CU
0195      CU=10.*ALOG10(CU)
0196      XSU=10.*ALOG10(XSU)
0197      IF(IRVTU(I1).EQ.1) GO TO 136
0198      VIU(I1)=UI
0199      IF(KPRNT.EQ.0)
0200      1 PRINT 56,UI,CVNUI,CU,XSU)
0201      56 FORMAT(' UP-LINK: I =',F9.1,' PWOP, C/N =',F9.1,' DB, C =',
0202      1 F9.1,' DBW, X/P SUM =',F9.1,' DBW//')
0203      GO TO 140
0204      136 XDC=-10.*ALOG10(UI)

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0196      VIU(II)=XQC
0197      IF(KPRNT,FQ,0)
0198      58 FJRMAT( ' UP-LINK: QC/X =', F9.1, ' DB, C/N =', F9.1, ' DB, C =',
140      1F9.1, ' DBW, X/Q SUM =', F9.1, ' DBW'//)
0199      CONTINUE
0200      KGRCV=IGRCV(II)
0201      IF(KGRCV,FQ,0) KGRCV=1
0202      KRMN=KRMX+1
0203      KRMX=KRMX+KGRCV
0204      K2=IAM(II)
0205      F1=FS(II)
0206      DO 70 KK=KRMN,KRMX
0207      I2=IGD(KK)
0208      AA=AS(I2,1)
0209      AQ=A(I2,1)
0210      DEL=0.
0211      GAM=0.
0212      IPAT1=IPTGD(KK)
0213      IPAT2=IPATS(II)
0214      DLPS=DST(II)
0215      IF(K2,EQ,I2) GO TO 48
0216      IF(ELPT(III,EQ,0.) GO TO 134
0217      JIFPT=0
0218      IF(II,LE,NFIX) GO TO 133
0219      JIFPT=JLLPT
0220      IF(JLLPT,FQ,0) GO TO 133
0221      FTPTL=FPL(II)
0222      FTPTR=FPR(II)
0223      133 CONTINUE
0224      CALL ELLPS(RS(II),RG(K2),ELG(K2),RG(I2),ELG(I2),
1 DST(III),FLPT(II),DLPS)
0225      134 CONTINUE
0226      IF(K2,GT,I2) GO TO 46
0227      PS=SPS(I2,K2)
0228      GO TO 47
0229      46 PS=SPS(K2,I2)
0230      47 DEL=ARCSIN(AS(K2,1)+AA-PS)/(A(K2,1)*AQ*2.11
0231      48 CALL GAIN(GAM,DEL,IPAT1,IPAT2,1,1,F1,PE,DGR(KK),DST(II),ELPT(II),
1 DLPS,ETAG(KK),ETAS(II),IBW,GANE)
0232      CD=GANE*PWD(II)*CS/(PI*45*AA*F1**2) /ERUMS
0233      TMP=TD1
0234      IF(II,GT,NFIX) TMP=TD51
0235      CVNRD=RDL*TMP*WRFD(III)/CD
0236      CVNDI=-10.*ALOG10(CVNRD)
0237      CVND(KK)=CVNDI
0238      TTCVN=-10.*ALOG10(CVNRU+CVNRD)
0239      TCVN(KK)=TTCVN
0240      XSD=0.
0241      DO 45 JJ=1,NLNK
0242      IF(JJ,EQ,II) GO TO 45
0243      J=IS(JJ)
0244      J2=IAM(JJ)
0245      A2=2.*A(I2,J)
0246      ASX=AS(I2,J)
0247      IF(J,GT,I) GO TO 41
0248      SS=SPS(J,I)
0249      GO TO 42

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0250      41 SS=SPS(I,J)
0251      42 IF(J2.GT.12) GO TO 43
0252      PS=SPS(I2,J2)
0253      GO TO 44
0254      43 PS=SPS(I2,I2)
0255      44 CAM=ARCCOS((A4+ASX-SS)/(AQ*A2))
0256      DEL=ARCCOS((ASX+AS(I2,J)-PS)/(A(I2,J)*A2))
0257      IF(ELPT(IJJ).EQ.0.) GO TO 144
0258      JIFPT=0
0259      IF(IJJ.LE.NFIX) GO TO 143
0260      JIFPT=JLLPT
0261      IF(JLLPT.EQ.0) GO TO 143
0262      FTPTL=FPL(IJ)
0263      FTPTL=FPR(IJ)
0264      143 CONTINUE
0265      CALL FLLPS(PS(IJ),RG(IJ2),ELG(IJ2),RG(I2),ELG(I2),
      1 DST(IJJ),ELPT(IJJ),DLPS)
0266      144 CONTINUE
0267      IPAT2=IPATS(IJJ)
0268      CALL GAINIGAM,DEL,IPAT1,IPAT2,IPLO(I1),IPLO(IJJ),F1,PEN,
      1 DGRIKK),DST(IJJ),ELPT(IJJ),DLPS,ETAG(KK),ETAS(IJJ),TRW,GANE)
0269      X=PWO(IJJ)*CS*GANE/(PI4S*ASX*F1*F1)/ERUMS
0270      CALL RTC(DND(I1),DND(IJJ),WRFO(I1),WRFO(IJJ),FS(I1),FS(IJJ)
      1,IPVTD(I1),IRVTD(IJJ),SPONW,R)
0271      XSD=XSD+X/R
0272      IF(KPRNT.NE.0) GO TO 45
0273      EI=X/(R*CD)
0274      RDR=10.*ALOG10(P)
0275      XDR=10.*ALOG10(X)
0276      GDR=10.*ALOG10(GANE)
0277      IF(IRVTD(I1).EQ.1) GO TO 145
0278      RDR=RDR+90.
0279      PRINT 51,IJJ,EI,XDR,RDR,GDR
0280      GO TO 45
0281      145 EI=-10.*ALOG10(F1)
0282      PRINT 52,IJJ,EI,XDR,RDR,GDR
0283      45 CONTINUE
0284      IF(KPRNT.EQ.0)
      1PRINT 65,I1,CHR(KK),ELG(I2),RG(I2),RS(I1)
0285      65 FORMAT(1,' DOWN-LINK ',I3,',',45,' AT ',2F8.2,' FROM SATELLITE AT
      1',F8.2)
0286      DI=XSD/CD
0287      TOTI=UI+DI
0288      CD=10.*ALOG10(CD)
0289      XSD=10.*ALOG10(XSD)
0290      IF(IRVTD(I1).EQ.1) GO TO 146
0291      VID(KK)=DI
0292      VTCT(KK)=TOTI
0293      IF(KPRNT.EQ.0)
      1PRINT 66,DI,CVNDI,CD,XSD,TOTI,TTCVN
0294      66 FORMAT(1,' DOWN-LINK: I =',F9.1,' PWOP, C/N =',F9.1,' DB, C =',
      1,F9.1,' DBW, X/R SUM =',F9.1,' DBW/' TOTAL I =',F9.1,' PWOP,
      2TOTAL C/N =',F9.1,' DB'//)
0295      GO TO 150
0296      146 XDC=-10.*ALOG10(DI)
0297      TOTI=-10.*ALOG10(TOTI)
0298      VID(KK)=XDC
0299      VTCT(KK)=TOTI

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0300      IF(KPRNT.EQ.0)
0301      1PRINT 68,XGC,CVNDI,CD,XSD,TOT1,TTCVN
0301      68 FORMAT(' DOWN-LINK: QC/X =',F9.1,' DB, C/N =',F9.1,' DB, C =',
0301      1,F9.1),' DPW, X/Q SUM =',F9.1,' DBW'/' TOTAL C/X =',F9.1,' DB,
0301      2TOTAL C/N =',F9.1,' DB'//)
0302      150 CONTINUE
0303      70 CONTINUE
0304      IF(KPRNT.EQ.0) PRINT 57
0305      57 FORMAT(/5X,25('*****'))
0306      60 CONTINUE
0307      PRINT 54,TITL
0308      PRINT 82
0309      82 FORMAT(/18X,'G.S.DIA. SAT.DIA.1 SAT.DIA.2 FREQUENCY BANDWIDTH
0309      1 EFFICIENCY POWER # CHANNELS TEMPERATURE POL. G-PAT-S')
0309      DO 75 I=1,NLNK
0311      TMP=TDI
0312      IF(I.GT.NFIX) TMP=TDSEI
0313      75 PRINT 83,I,DGT(I),DSR(I),ELPR(I),FG(I),WRFU(I),ETAG(I),PWU(I)
0313      1, UNQ(I),TUI,IPLU(I),IPTGU(I),IPATS(I)
0313      2 ,DGP(I),OST(I),FLPT(I),FS(I),WREF(I),ETAS(I),PWD(I),ONO(I)
0313      3,TMP,IPLD(I),IPTGD(I),IPATS(I)
0314      83 FORMAT(/18,' UP ',6F11.3,3(F10.0,2X),3I5/9X,'DOWN',6F11.3,3(F10.0
0314      1,2X),3I5)
0315      IF(NFIX.GT.0)
0315      1PRINT 71,(RS(I),I=1,NFIX)
0316      71 FORMAT(/10X,'FIXED SATELLITE LONGITUDES'/(/6F15.3))
0317      N1=NFIX+1
0318      IF(NS.GE.N1)
0318      1PRINT 72,(RS(I),I=N1,NS)
0319      72 FORMAT(/10X,'BROADCAST SATELLITE LONGITUDES'/(/6F15.3))
0320      PRINT 54,TITL
0321      54 FORMAT(1H1,10X,20A4)
0322      PRINT 84
0323      84 FORMAT(/11X,'WANTED LINK',11X,'UP-LINK',5X,'UP-LINK',7X,'DOWN-LINK
0323      1',3X,'DOWN-LINK',8X,'TOTAL',7X,'TOTAL'/30X,'INTERFERENCE',5X,'C/N'
0323      2,7X,'INTERFERENCE',5X,'C/N',7X,'INTERFERENCE',5X,'C/N')
0324      KRMX=0
0325      DO 80 I=1,NLNK
0326      II=IGUII)
0327      PRINT 86
0328      86 FORMAT(1H )
0329      KGRCV=IGRCV(I)
0330      IF(KGRCV.EQ.0) KGRCV=1
0331      KRMN=KRMX+1
0332      KRMX=KRMX+KGRCV
0333      DO 80 K=KRMN,KRMX
0334      80 PRINT 85,I,NAM(I),CHR(K),VIU(I),CVNU(I),VID(K),CVND(K),VTOT(K),
0334      1 TCVN(K)
0335      85 FORMAT(110,A6,' TO',A5,3(3X,2F12.1))
0336      NCAS=NCAS+1
0337      IF(NCAS.GT.NCSX) GO TO 10
0338      320 CONTINUE
0339      READ 3,TITL
0340      READ (5,2,END=999) (RS(I),I=1,NS)
0341      GO TO 300
0342      999 CALL EXIT
0343      END

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0001      SUBROUTINE ELLPS(RS, RA, ELA, RG, ELG, D1, D2, DLPS)
0002      REAL*4 L1, L2, M1, M2, N1, N2
0003      COMMON G(4), FTPTL, FTPTR, ILLPT
0004      DATA RPD/1.745329E-2/, D/6.617/
0005      RSR=RS*RPD
0006      XS=D*COS(RSR)
0007      YS=D*SIN(RSR)
0008      RAR=RA*RPD
0009      CRA=COS(RAR)
0010      SRA=SIN(RAR)
0011      ELAR=ELA*RPD
0012      ELA=COS(ELAR)
0013      ZA=SIN(ELAR)
0014      RGP=RG*RPD
0015      ELGR=ELG*RPD
0016      CLG=COS(ELGR)
0017      ZG=SIN(ELGR)
0018      XA=CLA*CRA
0019      XAS=XA-XS
0020      YA=CLA*SRA
0021      YAS=YA-YS
0022      XGS=CLG*COS(RGR)-XS
0023      YGS=CLG*SIN(RGR)-YS
0024      L2=ZG*YAS-ZA*YGS
0025      M2=ZA*XGS-ZG*XAS
0026      N2=XAS*YGS-XGS*YAS
0027      IF(ILLPT.EQ.0) GO TO 10
0028      FLR=FTPTL*RPD
0029      FRR=FTPTR*RPD
0030      CLF=COS(FLR)
0031      XFA=CLF*COS(FRR)-XA
0032      YFA=CLF*SIN(FRR)-YA
0033      ZFA=SIN(FLR)-ZA
0034      L1=YAS*ZFA-ZA*YFA
0035      M1=ZA*XFA-XAS*ZFA
0036      N1=XAS*YFA-YAS*XFA
0037      GO TO 20
0038      10 CONTINUE
0039      L1=-CRA*ZA
0040      M1=-SRA*ZA
0041      N1=CLA-D*COS(RAR-RSR)
0042      20 CONTINUE
0043      DEN=SQRT((L1*L1+M1*M1+N1*N1)*(L2*L2+M2*M2+N2*N2))
0044      COSP=((L1*L2+M1*M2+N1*N2)/DEN)
0045      D2S=D2*D2
0046      IF(ILLPT.EQ.2) GO TO 25
0047      DLPS= D1*D2/SQRT(D2S+COSP*COSP*(D1*D1-D2S))
0048      RETURN
0049      25 D1S=D1*D1
0050      DLPS= D1*D2/SQRT(D1S+COSP*COSP*(D2S-D1S))
0051      RETURN
0052      END

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0001      SUBROUTINE RTC( N1, N2, W1, W2, F1, F2, IR1, IR2, SPONW, R)
0002      REAL*4 IPXIW, M1, M2, MS, MIS, N1, N2, MU
0003      DATA CPRT, RTIO, CFM/5.013257, .3162278, .0042/
0004      DATA IPXIW/4.466912/, CFMTV/4.2/
0005      IF(IR2.EQ.2) GO TO 10
0006      FD=F1-F2
0007      FO=FD*1.E3
0008      FM2=CFM*N2
0009      IF(IR1.EQ.1) GO TO 40
0010 10 CONTINUE
0011      CON=42.8
0012      IF(N1.LT.240.) CON=1.7*N1**.6
0013      FM1=CFM*N1
0014      M1=RTIO*(.5*W1/FM1-1.)
0015      MIS=M1*M1
0016      IF(IR2.EQ.2) GO TO 35
0017      V=FO/FM1
0018      M2=RTIO*(.5*W2/FM2-1.)
0019      MS=M2*FM2/FM1
0020      MS=MIS+M2*MS
0021      IF(IR2.EQ.1) GO TO 20
0022      DEN=EXP(-.5*(1.+V)**2/MS)+EXP(-.5*(1.-V)**2/MS)
0023      R=CPRT*IPXIW*MS*SQRT(MS)/DEN
0024      GO TO 30
0025 20 CONTINUE
0026      DFAC=3.145+1.7*MIS
0027      DEN=EXP(-(1.+V)**2/DFAC)+EXP(-(1.-V)**2/DFAC)
0028      R=IPXIW*(.2+.8*MIS*M1)/DEN
0029 30 R=P*CON*1.E-9
0030      RETURN
0031 35 R=2.*MIS*(M1/RTIO+1.)*IPXIW
0032      GO TO 30
0033 40 CONTINUE
0034      IF(ABS(FD).GE..5*(W1+W2)) GO TO 65
0035      FM1=CFMTV
0036      M1=.5*W1/FM1-1.
0037      IF(IR2.EQ.2) GO TO 55
0038      IF(FD.LT.0.) FD=-FD
0039      IF(IR2.EQ.0) GO TO 50
0040      R=1.
0041      IF(FD.EQ.0.) RETURN
0042      M2=.5*W2/FM1-1.
0043      MU=M1/M2
0044      QDR=FO/M1**.85+.475*ALOG10(MU)/MU**2.5*FD**(.645*MU)
0045 44 R=10.**(.1*QDR)
0046      RETURN
0047 50 CONTINUE
0048      M2=.5*W2/FM2-1.
0049      M2=.42*(FM2/FM1)**1.5
0050      MU=M1/M2
0051      QDR=5.4
0052      IF(FD.EQ.0.) GO TO 44
0053      QDR=QDR+FD/M1**1.15+.85*ALOG10(MU)/MU**3*FD**(.5*MU)
0054      GO TO 44
0055 55 R=10.**4.03*IPXIW*(M1+1.)/SPONW
0056      RETURN
0057 65 R=1.E10
0058      RETURN
0059      END

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0001      SUBROUTINE GAIN (TH1, TH2, I1, I2, IPL1, IPL2, F, PE, D1, D2, DX, DLPS,
0002      1 ETAL, ETA2, IRW, GANE)
0003      DIMENSION G(4)
0004      COMMON G
0005      DATA DPR, PHI, PI, PI2/57.29578, 1.570796, 3.141593, 6.283185/
0006      DATA FTOM/0.3048/, CC/40.5/
0007      IGO=I1
0008      J=1
0009      D=D1*FTOM
0010      DS=D*D
0011      DU=D
0012      ETA=ETA1
0013      ETART=SQRT(ETA)
0014      PHO=14.43825/(ETART*DU*F)
0015      PHE=PE*PHO
0016      PHI=TH1
0017      1 CONTINUE
0018      GO=109.6623*ETA*DS*F*F
0019      GOLG=ALOG10(GO)
0020      PHI=PHI+PHE
0021      IF (PHI.LT.0.) PHI=0.
0022      PHID=PHI*DPR
0023      FIRAT=PHID/PHO
0024      IF (PHI.EQ.0.) GO TO 220
0025      FRLG=ALOG10(FIRAT)
0026      IF (FIRAT.GT.0.5) GO TO 10
0027      U=10.47198*ETART*DU*F*SIN(PHI)
0028      USU=SIN(U)/U
0029      G4=G0*(.9976*USU**2.25+.0024)
0030      G(J)=G4
0031      GO TO 100
0032      10 GO TO (20,30,40,50,50,51,60), IGO
0033      *** EARTH STATIONS, SIDE LOBES, CO-POLARIZED
0034      20 CONTINUE
0035      *** BROADCASTING SATELLITE SERVICE, COMMUNITY RECEPTION
0036      GL=GOLG-1.05-2.5*FRLG
0037      GPH=1.
0038      IF (GL.LE.0.) GO TO 95
0039      GO TO 94
0040      30 CONTINUE
0041      *** BROADCASTING SATELLITE SERVICE, INDIVIDUAL RECEPTION
0042      GL=GOLG-.9-2.*FRLG
0043      GMIN=0.
0044      IF (GOLG.GT.3.) GMIN=GOLG-3.
0045      IF (GL.LT.GMIN) GL=GMIN
0046      GPH=1.
0047      IF (GL.EQ.0.) GO TO 95
0048      GO TO 94
0049      40 CONTINUE
0050      *** FIXED SATELLITE SERVICE
0051      PHOL=ALOG10(PHO)
0052      PHLG=ALOG10(PHID)
0053      IF (FIRAT.GE.1.5) GO TO 45
0054      GND=3.2-2.5*(PHOL+0.17609)
0055      IF (PHO.GT.0.6666666) GND=GND+0.176+PHOL
0056      ***** IF PHO < 2/3, D/LAMBDA > 100
0057      GST=GOLG-0.3
0058      GL=GST+(GND-GST)/0.47712*(FRLG+0.30103)

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0053      GO TO 48
0054      45 GL=3.2-2.5*PHLG
0055      IF(PHD.GT.0.6666666) GL=GL+0.176*PHDL
C      ***** IF PHD > 2/3, P/LAMBDA < 100
0056      48 GPH=0.1
0057      IF(GL.LE.-1.) GO TO 95
0058      GO TO 94
C      *** SATELLITES, SIDE LOBES, CO-POLARIZED
0059      50 CONTINUE
C      *** BROADCASTING SATELLITE SERVICE
C      *** NORMAL LOBE CONTROL
C      *** CONSTANTS FOR NORMAL SIDE-LOBE CONTROL
0060      C2=1.0926
0061      C3=3.8019
0062      GO TO 52
0063      51 CONTINUE
C      *** CONSTANTS FOR LIMIT OF SIDE-LOBE CONTROL
0064      C2=1.4251
0065      C3=15.136
0066      52 IF(FIRAT.GT.0.81193) GO TO 53
C      *** (NO LOBE CONTROL - #55 ONLY)
0067      55 GL=GOLG-1.05-2.5*FRLG
0068      GO TO 58
0069      53 IF(FIRAT.GT.C2) GO TO 54
0070      GL=GOLG-2.-13.*FRLG
0071      GO TO 58
0072      54 IF(FIRAT.GT.C3) GO TO 55
0073      GL=GOLG-2.5
C      *** (LIMIT OF SIDE-LOBE CONTROL)
0074      IF((GO.EQ.6) GL=GL-1.5
0075      58 GPH=1.
0076      IF(GL.LE.0.) GO TO 95
0077      GO TO 94
0078      60 CONTINUE
C      *** FIXED SATELLITE SERVICE
0079      IF(FIRAT.GT.1.291) GO TO 61
0080      GL=GOLG-1.2*FIRAT*FIRAT
0081      GO TO 68
0082      61 IF(FIRAT.GT.3.1623) GO TO 62
0083      GL=GOLG-2.
0084      GO TO 68
0085      62 GL=GOLG-.75-2.5*FRLG
0086      68 GPH=.1
0087      IF(GL.LE.-1.0) GO TO 95
0088      94 GPH=10.**GL
0089      95 G(J)=GPH
0090      100 CONTINUE
0091      IF(IPL1.EQ.IPL2) GO TO 195
0092      IF(FIRAT.GT.0.392857) GO TO 141
0093      DELGX=3.5
0094      GO TO 145
0095      141 IF(FIRAT.GE.1.107143) GO TO 142
0096      DELGX=4.6-2.8*FIRAT
0097      GO TO 145
0098      142 DELGX=1.5
0099      145 IF(IBW.EQ.2) DELGX=DELGX-0.5
0100      G(J+2)=G(J)/10.**DELGX
0101      195 IF(J.EQ.2) GO TO 101

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FORTRAN IV G LEVEL 21

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0102      IGC=12
0103      J=J+1
0104      D=D2*FTOM
0105      DS=D*D
0106      DU=D
0107      ETA=ETA2
0108      ETART=SQRT(ETA)
0109      PHO=14.43825/(ETART*DU*F)
0110      PHI=TH2
0111      PHE=PE
0112      IF(DX.EQ.0.) GO TO 1
0113          DS=D*DX*FTOM
0114          DU=DL*PS*FTOM
0115      PHO=14.43825/(ETART*DU*F)
0116      GO TO 1
0117 101 IF(IPL1.EQ.IPL2) GO TO 210
0118 201 GANE=G(1)*G(4)+G(2)*G(3)
0119      RETURN
0120 210 GANE=G(1)*G(2)
0121      RETURN
0122 220 G(J)=GO
0123      GO TO 100
0124      END
```

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